

AlloyBot: On-Demand Synthesis of Bulk Alloys by Automatic Arc-Melting

Vignesh Selvaraj

University of Wisconsin-Madison <https://orcid.org/0000-0002-4890-7264>

Pakorn Boonpetch

University of Wisconsin-Madison

Anagh Dutta

University of Wisconsin-Madison

Ming En Pek

University of Wisconsin-Madison <https://orcid.org/0000-0002-4733-5436>

Sebastian Alexander Kube

`sebastian.kube@wisc.edu`

University of Wisconsin-Madison <https://orcid.org/0000-0001-8167-4178>

Method Article

Keywords: arc-melting synthesis, laboratory automation, self-driving laboratory, autonomous materials science, accelerated alloy development

Posted Date: May 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9761885/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Preprint

AlloyBot: On-Demand Synthesis of Bulk Alloys by Automatic Arc-Melting

Vignesh Selvaraj ^a, Pakorn Boonpetch ^a, Anagh Dutta ^a, Ming En Pek ^a,
Sebastian A. Kube ^{a,*}

^a Department of Materials Science and Engineering, University of Wisconsin-Madison,
Madison, WI 53706, USA

* Corresponding author. E-mail address: sebastian.kube@wisc.edu

Keywords

arc-melting synthesis, laboratory automation, self-driving laboratory, autonomous materials science, accelerated alloy development

Abstract

Developing new high-performance alloy compositions is expensive and time-consuming. Conventional experimental alloy testing performed manually by human researchers is a primary bottleneck. To overcome this, we are building “AlloyBot”, a self-driving laboratory that can autonomously synthesize and test alloys 100× faster. Here we present the first building block: a fully automatic weighing and arc-melting system that can synthesize 1 alloy per hour (>150 alloys per week). Various innovations facilitate this process, such as a load-lock system to rapidly exchange crucibles, and four electrodes used for arc-melting. Alloys can be synthesized as buttons or cast rods, up to 25cm³ in volume (>100g Ti-6Al-4V), and at a unit cost broadly ranging around ~100 USD/5cm³, driven primarily by feedstock pricing rather than human labor. Within metallurgical constraints, any element combination and composition can be synthesized on-demand. Performance is validated through the synthesis of Ti-6Al-4V alloy, Ti₂₀Zr₂₀Hf₂₀Nb₂₀Ta₂₀ refractory high-entropy alloy, and Zr₅₅Cu₃₀Ni₅Al₁₀ metallic glass.

1. Introduction

Across manufacturing, energy, aerospace, and defense technologies, new alloy materials are urgently needed to withstand increasingly extreme operating conditions. In developing turbines and jet engines ¹⁻³, novel propulsion systems ^{4,5}, high-speed aerospace vehicles ⁶, nuclear reactors ^{7,8}, and emerging technologies such as geothermal energy ⁹, progress is often constrained by the lack of structural alloys and coatings which can survive increasingly demanding combinations of high mechanical stresses, extreme temperatures, oxidative and corrosive environments, intense radiation, long-term cyclic exposure, and beyond.

Here lies the problem: Alloy development is too slow to meet the mounting technological demands. While new alloy design concepts provide ample opportunities to develop new alloys with superior performance (e.g., multi-principal-element compositions ¹⁰⁻¹², novel processing methods ¹³⁻¹⁶, metastability ¹⁷⁻²⁰, architected structures ²¹⁻²⁶), it remains a challenge to efficiently navigate the vast potential design space and discover those rare alloys which successfully balance multiple property objectives at once. Indeed, Integrated Computational Materials Engineering (ICME) and Artificial Intelligence (AI) recently provide powerful tools to accelerate alloy discovery. But their predictive accuracy often remains limited, especially for underexplored multicomponent composition regions, for cases where different mechanisms compete across length-scales and time-scales, and when materials face multiple extreme conditions simultaneously.

Experimental alloy testing is therefore indispensable to obtain ground-truth information about complex alloy behavior. In the conventional approach, however, experimental alloy testing is an expensive and time-consuming process, because it relies on human researchers to manually synthesize, process, characterize, and test alloy specimens. New strategies are needed to make alloy development scalable and orders of magnitude faster.

Motivated by this, we are building “AlloyBot”, an autonomous, self-driving laboratory which uses robotics, automation, and AI to develop alloys for extreme operating conditions over 100 times faster. In this article, we present the first building block: an automatic weighing and arc-melting system for the on-demand synthesis of bulk alloys.

Table 1 summarizes the performance objectives that have guided the development of this system. Here, we selected arc-melting as the synthesis method best aligned with these objectives. Arc-melting is widely accepted as the gold-standard lab-scale method to synthesize high-quality bulk alloys across diverse compositions. To provide a simple overview of arc-melting: Feedstock material is melted and homogenized inside a high-purity argon atmosphere by means of a hot plasma arc generated by passing electric current between a tungsten-electrode tip and a water-cooled copper hearth (similar to TIG welding) ²⁷. While arc-melting has been in use for decades, it is still predominantly conducted in low-throughput manual operation by human researchers. Some effort has been made to streamline selected aspects of arc-melting synthesis ²⁸⁻³³, but to date no system has been published that meets the objectives defined in Table 1.

Indeed, automating bulk alloy synthesis is no trivial task: Designing equipment to accurately dispense solid metal feedstock, maintain clean contamination-free environments, and process metals at temperatures even exceeding 3400°C along with the associated power and footprint requirements is inherently challenging. On top of this, it is often not obvious how automatic materials handling, process control, and feedback can be built into such processes. As a result, automation in alloy

synthesis is currently much less developed compared to other areas of materials and chemical synthesis ^{27,34–36}, e.g. compared to wet chemistry where dispensing is routinely automated by comparatively affordable pipetting robots and at moderate temperatures.

Broadly speaking, automatic arc-melting could be realized along two complementary paths, which will likely evolve in parallel over the coming years: Firstly, existing human-oriented arc-melting systems could be automated by teaching robots to perform synthesis steps exactly as humans would. This approach is currently being pioneered by Fensin *et al.* ³⁷ and offers the flexibility to adopt existing human-facing tools without expensive modifications. Secondly, arc-melting systems could be redesigned from the ground up to eliminate human-oriented features, make process control more robust, and enable higher throughput. This is the approach chosen for our system ³⁸. The following article describes in detail how the objectives defined in Table 1 are met. To gain an intuitive sense for the operation of the system, the reader is further invited to view associated video material enclosed as part of the Supplementary Information.

Table 1. Objectives guiding the development of the automatic synthesis system presented here.

Objective	Details and Metrics
Fully autonomous synthesis	Require no human assistance, except <1 hour of maintenance once per day.
Effective throughput: 1 alloy per hour	Equivalent to >150 alloys per week.
On-demand synthesis	Deliver new alloy within 3 hours of request.
Alloys in bulk-form	Enable meaningful subsequent testing. E.g.: • thermo-mechanical processing towards equilibrium microstructures • mechanical and oxidation behavior as length-scale sensitive properties
Alloy volume: Up to 25 cm ³	Equivalent to >100 g of Ti-6Al-4V. Enable preparation and testing of large specimens when needed.
Feedstock dispensing: Any target composition amongst ≥12 metallic elements	Enable unconstrained probing of multicomponent composition spaces (e.g., multi-principal element alloys, metallic glasses).
Dispensing accuracy: Better than 1 at.%	Enable probing highly composition-sensitive properties (e.g., glass forming ability ³⁹).
Feedstock procurable in standardized, low-cost, high-purity form	Avoid powders due to concerns of availability, cost, impurity pickup, containment, health, and safety.
High-quality specimens for lab-scale metallurgical investigation	Uniform composition (notwithstanding micro-segregation from solidification), low impurity concentrations, no major defects.

2. Results

2.1 System Overview

Figure 1 provides an overview of our system, which is comprised of three principal components: **(A)** A six-axis robotic arm is equipped with a custom gripper to facilitate pick-and-place operations within and between the modules. The robot is further mounted on a horizontal 7th axis to expand its reach, allowing it to drive to individual AlloyBot modules. **(B)** The automatic weighing module is purpose-built to dispense pure elemental feedstock materials at a compositional accuracy much better than 1 at.%. After dispensing, the elemental feedstock materials are stacked into a reusable copper crucible, which serves a dual purpose both as transfer container and as melting container. Next, the robot transfers the crucible into **(C)** the automatic arc-melting module. Specifically, the crucible is first loaded into the load-lock chamber and then moved by an automatic transfer mechanism through a gate valve and into the melting chamber. The material inside the crucible undergoes multiple cycles of automatic melting, flipping, and remelting for homogenization, as well as an optional suction-casting step at the end. Finally, the crucible is unloaded from the arc-melting module, the robot retrieves the alloy button or cast rod, and passes it on for subsequent experiments.

Additional components include “AlloyBotMaster”, an industrial PC which acts as supervisory controller to coordinate the interaction between the robot, weighing module, and arc-melting module. Also integrated is the “AlloyBotBrain” PC, which can stream, process, analyze, and store metadata and process data generated by the weighing and arc-melting modules. In combination, the above components form an integrated system to synthesize alloys at specified compositions on demand.

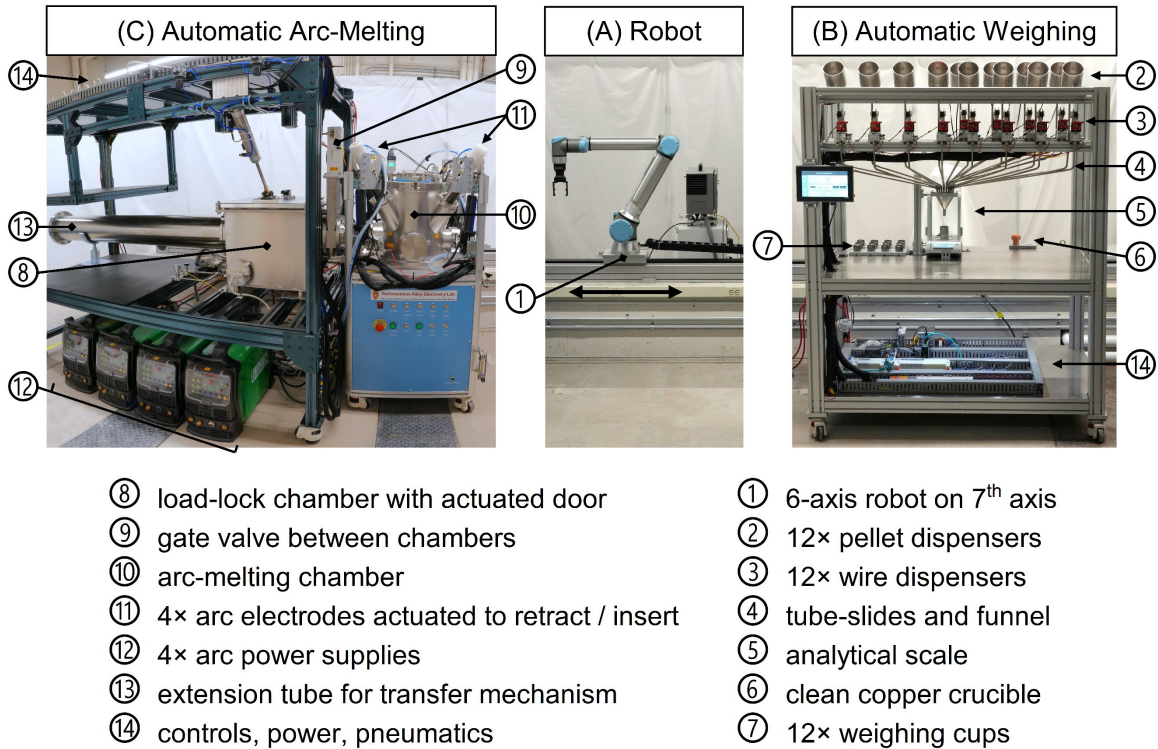


Fig.1. Overview of the AlloyBot automatic weighing and arc-melting system, with principal and sub-components labeled.

2.2 Automatic Weighing Module

The weighing module is designed to automatically dispense pure elemental feedstock materials at the exact masses needed to produce a desired target composition. For this purpose, we have designed and manufactured two types of feedstock dispensing mechanisms. Firstly, pellet dispensers (Fig.2a) are stocked with pellets (~3 mm size, commercially available as evaporation materials), which are then singulated by a rotating-disk mechanism. These pellets allow to dose elements in coarse, discrete mass increments and are comparatively cost-effective. Secondly, wire dispensers (Fig.2b) are stocked with spooled wire (0.5 to 1.0 mm diameter), which is fed by pinch-rollers into a cutting mechanism (Fig.2c) to dispense short wire segments of precisely controlled length. This allows to dose elements in fine, variable mass increments, but is less cost-effective given the higher specific cost of wire compared to pellets.

To balance compositional accuracy and cost, the Weighing Module utilizes one pellet + wire dispenser pair for each element. In the first step, pellets are dispensed to incrementally approach a given target mass as closely as possible without exceeding it. In the second step, the remaining mass to target is dispensed as wire pieces of precisely controlled length and mass. From the dispensers, the pellets and wire pieces slide down through stainless steel tubing and into a funnel, from where they finally drop into a weighing cup, which is positioned on a balance to provide closed-loop mass feedback.

In its current form, the weighing module is equipped with 12 pellet + wire dispenser pairs to enable on-demand dispensing of any composition amongst the 12 stocked constituent elements. The module is built for easy expansion up to 24 dispenser pairs in the future. Future implementations will also incorporate additional feedstock dispenser types, e.g. for brittle elements (e.g., silicon), compound materials (e.g., oxides, nitrides, carbides), and master alloys, which are often only available as granules of irregular size and shape.

The overall weighing workflow involves the following steps: (1) The robot places a clean copper crucible into the stacking position on the weighing module. (2) The weighing module receives the command to weigh out feedstock in amounts equivalent to a defined target alloy composition and volume, and (3) calculates the corresponding target masses for the individual constituent elements. Then, for each constituent element (4) the robot places one weighing cup on the scale (Fig.2d), the weighing module dispenses pellets and wire pieces into the weighing cup up to the target mass (Fig.2e), and then the robot sets the weighing cup aside. Once all constituent elements have been prepared in this manner, (5) the robot sequentially picks the weighing cups and carefully tilts them to pour their feedstock contents into the copper crucible (Fig.2f). Following common practice, for best melting results the robot places low melting temperature elements towards the bottom of the crucible and stacks higher melting temperature elements to the top. (6) Finally, the robot transfers the crucible to the arc-melting module. This concludes one weighing cycle and can be completed within less than 1 hour (Fig.7).

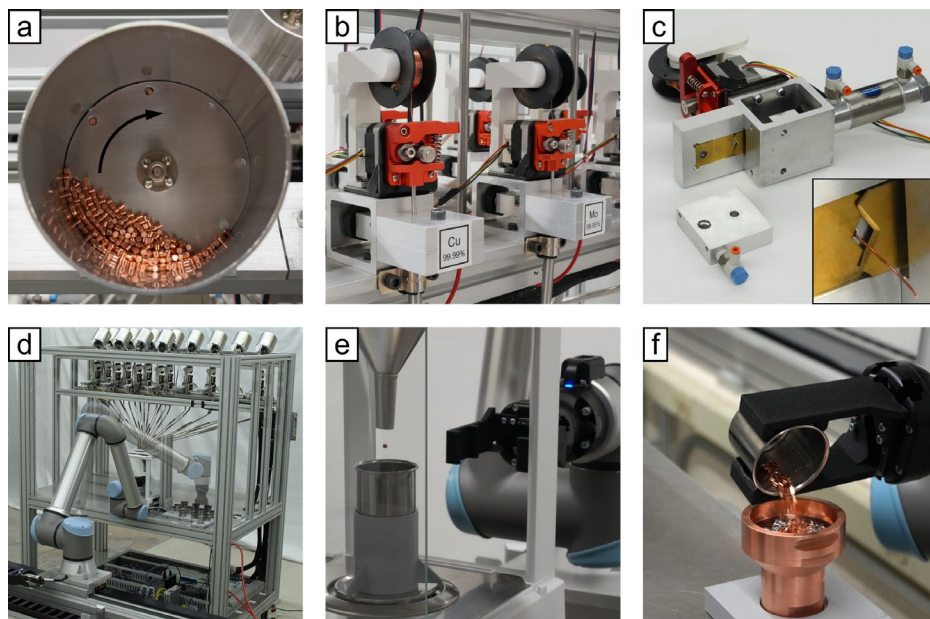


Fig.2. Automatic weighing module details. **(a)** At the base inside each pellet dispenser is a rotating disk, which is driven by a stepper-motor. Along its circumference, the disk features eight circular holes to capture single pellets. Every time the disk advances by $1/8^{\text{th}}$ of a revolution, one pellet passes the 12-o'clock position, where it drops through a rear opening and into a tube-slide. **(b)** Each wire dispenser holds a spool of wire (top), that is fed by a pair of pinch-rollers (middle) into a cutting mechanism (bottom), which is comprised of **(c)** a pair of pneumatically actuated v-blades (exposed by removal of lower casing here). After cutting, the wire segments are propelled down a tube-slide assisted by a compressed air pulse. All tube slides terminate into a single funnel mounted above a scale. **(d)** To receive pellet and wire feedstock, for each element the robot picks a dedicated weighing cup from the tray and places it under the funnel and onto the scale (rear-view here). **(e)** Pellets and wire segments are then dispensed via the funnel into the weighing cup, until the target mass is reached. **(f)** After all the required elements have been weighed out in this manner, the robot picks one cup at a time and pours its contents into a clean copper crucible, which serves as transfer and melting container in the subsequent arc-melting process.

For this approach, the achievable compositional accuracy can be estimated as a function of the total alloy volume and the molar densities of the constituent elements. In the simplest case, when an element is dispensed into an alloy of identical molar density, there is a direct correspondence between the element's volume fraction and the molar fraction it contributes. One ~ 3 mm feedstock pellet contributes ~ 2.5 at.% to a 1 cm^3 alloy, ~ 0.5 at.% to a 5 cm^3 alloy, and ~ 0.1 at.% to a 25 cm^3 alloy. For wire feedstock, segments can be reliably dispensed and weighed with a length accuracy better than 2 mm. One wire segment of 2 mm length and 1 mm diameter contributes ~ 0.16 at.% to a 1 cm^3 alloy, ~ 0.03 at.% to a 5 cm^3 alloy, and < 0.01 at.% to a 25 cm^3 alloy. Even better compositional accuracies can be achieved using smaller diameter wire.

Usually, however, molar densities between the constituent elements and target alloys will differ. In extreme cases where high molar density elements (e.g. Co, Ni 0.15 mol/cm^3) are dispensed into low molar density alloys (e.g. Y 0.05 mol/cm^3), this can alter the above composition increments by a factor of up to $3\times$. In a 5 cm^3 alloy, for example, one high molar density pellet would then contribute ~ 1.5 at.%, and one wire segment of 2 mm length would contribute ~ 0.05 at.%. This

underscores the need for the complementary use of pellet and wire feedstock, even when preparing large alloy volumes beyond 5 cm³.

Altogether, following this strategy the weighing module can dispense feedstock materials at a compositional accuracy significantly better than 1 at.% and across a wide range of constituent elements and target volumes.

As another key metric, the total feedstock cost of alloys can be estimated and optimized as a function of the target composition and volume. This is especially relevant in anticipation of “massive alloy testing campaigns”, which will incur significant feedstock cost when conducted across thousands of alloy compositions, as part of AlloyBot and similar self-driving laboratory platforms. In the first step, to minimize the cost per alloy, we note that the specific cost is typically greater for wire than for pellets. The consumption of wire, especially for expensive elements, should therefore be minimized. This can be achieved by allowing the target volume to vary within a small window and calculating the corresponding total cost. As illustrated in Fig.3a, the resulting volume-cost curves exhibit many segments where cost trivially increases with volume. More interestingly, however, these segments are separated by discontinuous drops in cost whenever a given length of expensive wire can be replaced by a full, more cost-effective pellet of the same element. Since experimental workflows can usually accommodate some small variation in the synthesized alloy volume, this strategy can unlock significant cost reductions, which range between 12 to 39% in our analysis (5th to 95th percentile amongst all 3dHEAs and RHEAs evaluated in Fig.3). In fact, in approximately half the cases, this strategy leads to a counter-intuitive result where cost is minimized by *increasing* the target volume. Fig.3a illustrates this through the example of Ti-6Al-4V, where increasing the target volume from 5.00 to 5.07 cm³ leads to a pronounced cost reduction from \$85 to \$58, because an expensive length of vanadium wire can be replaced by a full, more cost-effective vanadium pellet.

In the second step, we note that feedstock cost for alloys widely varies as function of composition, depending on the consumption of low versus high-cost elements. This makes it difficult to define a single unit cost value. Instead, Fig.3b-d therefore presents typical cost distributions calculated for three alloy classes of interest. These include High Entropy Alloys composed of 3d transition metals + Al (median: 74 USD/5cm³), Refractory High Entropy Alloys (median: 118 USD/5cm³ without Hf, 350 USD/5cm³ containing 20 at.% Hf), and Metallic Glasses (median: 78 USD/5cm³ for successful BMGs, 65 USD/5cm³ for all reported attempts). As an overall rule of thumb, for the 3dHEA and RHEA sets combined, the typical feedstock cost can be estimated at 103 USD/5cm³ (median), while noting that cost broadly ranges between 40 and 376 USD/5cm³ (5th to 95th percentile).

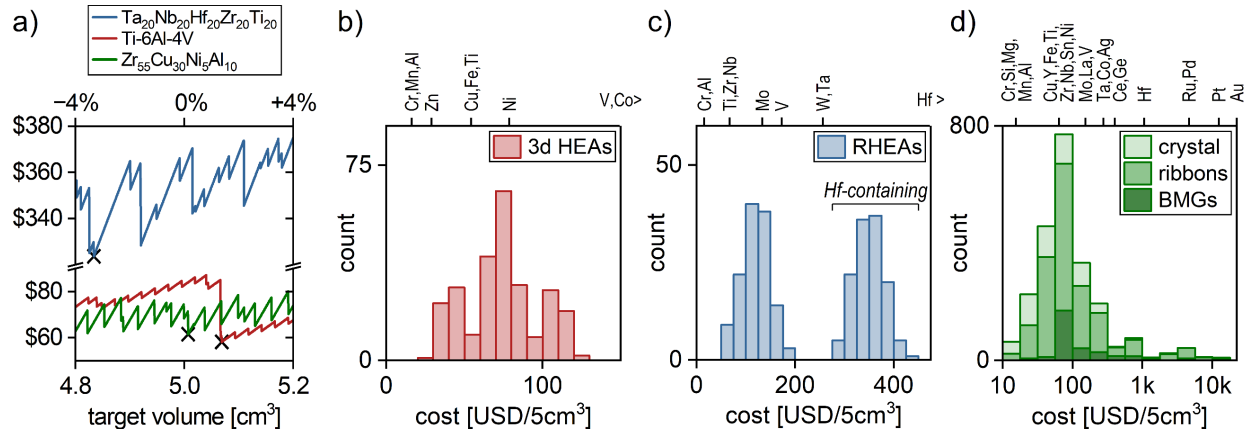


Fig.3. Feedstock cost analysis. (a) By allowing a small variation in target volume, cost can be reduced whenever a length of expensive wire can be replaced by a full, more cost-effective pellet of the same element. Cost is optimal at the minimum (x), which counter-intuitively is often found by increasing the target volume. Distributions of optimized cost are presented for (b) 3d High Entropy Alloys (cost of all possible equiatomic quinary combinations of Al,Ti,V,Cr,Mn,Fe,Co,Ni,Cu,Zn), (c) Refractory High Entropy Alloys (same for Al,Ti,V,Cr,Zr,Nb,Mo,Hf,Ta,W), and (d) metallic glasses (all compositions from combined, cleaned literature sets ^{40,41}) separated into bulk-glass-formers ("BMGs"), ribbon-glass-formers ("ribbons"), and reported unsuccessful glass synthesis attempts ("crystal"). For reference, the upper horizontal axes in (b-d) show the cost of pure element pellets. **Additional note:** It is common practice to quantify the amount of arc-melted material in units of mass. Given the wide range of densities, however, using units of volume is preferable, especially when subsequent experimental steps depend on the available volume of material (e.g. machine specimens of defined geometry from as-synthesized alloy). Here, the total volume is estimated based on the molar densities of the pure elements at standard conditions, while neglecting non-additivity in the mixed phase. The cost estimates here were generated based on small-lot pellet and wire pricing as either publicly listed or quoted to us (see Supplementary Table S1). Pricing is subject to market fluctuations and purchase volume.

2.3 Automatic Arc-Melting Module

The automatic arc-melting module is designed to accept the copper crucible containing the stacked feedstock, then melt, mix, and homogenize the feedstock into an alloy button, and optionally suction-cast the alloy into a rod. The conventional arc-melting approach embodied in most human-facing devices, however, does not lend itself particularly well to automation. Therefore, the arc-melting system presented here embodies several innovations which facilitate higher throughput and robust automation. These are described in detail below, both through schematic illustrations (Fig.4) and through photographs showcasing the physical implementation (Figs.5 and 6).

a) Electrode Configuration (Fig.4a):

Conventional: One electrode is used to generate a single arc. A human operator moves the electrode by hand to direct the arc onto the material, apply heat, and thus melt the material. Arc heating is localized, however, which can make uniform melting and homogenization difficult, especially for high-melting alloys and larger volumes. To achieve more uniform melting, the operator manually sweeps the arc in a circular motion across the material and targets unmolten regions based on visual observation and intuition.

Automation obstacles: Directly automating the conventional approach would require complex 3-axis electrode actuation, coupled with feedback to monitor melting and to guide the electrode. Meanwhile, issues of heating and melting uniformity would remain unresolved. Further, the process would remain under-constrained, making process control unnecessarily complex.

AlloyBot solution: Instead of a single electrode, we have implemented four electrodes, which are mounted at even spacing around the chamber wall and focused diagonally down at the hearth (similar to Czochralski arc-melting furnaces ⁴²). The electrodes are powered by individual power supplies to generate four independent arcs. As a result, heat is applied to the material from four directions and at a higher total power, yielding better melting uniformity especially for high melting temperature materials. Further, the melting operation itself requires no electrode motion and feedback. Rather, once focused onto the material, the electrodes can remain stationary. Simply by virtue of heat applied from four directions, the feedstock pieces naturally melt, merge, and mix into a single liquid droplet. This is further facilitated by the concave crucible floor, which centers the droplet and draws in unmelted feedstock from the perimeter. In addition, the diagonal mounting of the electrodes offers an unobstructed top-view of the melting process, which enables direct imaging feedback. Electrode currents can then be set to match the heating requirements of the target material.

Physical implementation: A top view of the melting sequence is shown in Fig.5. Initially, the electrodes are focused at the unmelted feedstock (Fig.5d). The arcs are then activated to heat and melt the feedstock, which merges into a single liquid alloy droplet (Fig.5e). Next, the arcs are turned off, the alloy is left to solidify (Fig.5f) and cool into a room temperature button (Fig.5g). During the melting process, output currents can optionally be time-modulated across electrodes to induce time-modulated magnetohydrodynamic flow, which is expected to enhance homogenization. For example, Fig.5i shows the arcs at a 20A base-current, with a 50A

peak-current circled in clockwise direction. While the electrodes do not need to be moved during the melting process, they are in fact actuated such that they can be positioned along a path composed of two segments (Fig.6e): Along the first segment, electrodes can be retracted longitudinally, such that the working distance between the electrode tip and the material can be adjusted both before and during the melting process. Along the second segment, electrodes can be retracted transversally, to provide the clearance necessary for crucible transfers.

b) Impurity Gettering (Fig.4b):

Conventional: To protect the target material from reacting with residual gaseous impurities such as O₂, N₂, or H₂O, it is common practice to purify the argon gas atmosphere inside the melting chamber using a getter. To this end, a piece of titanium is placed in a side pit on the hearth. During the melting process, the human operator then intermittently moves the arc away from the target material and onto the titanium getter. The getter is thus melted and kept at elevated temperatures to scavenge gas impurities.

Automation obstacles: On the one hand, the target material should be heated without interruptions to achieve uniform melting and homogenization. On the other hand, the titanium getter needs to be maintained at elevated temperature to serve its purpose. In practice, the human operator struggles to balance these goals by rapidly alternating between heating the target material and heating the getter. This makes the overall process discontinuous, hectic, and poorly controlled.

AlloyBot solution: To perform melting and gettering continuously and in parallel, these actions are separated between two independent components. Firstly, the arc-melting electrodes continuously heat the target material. Secondly, we designed a dedicated gettering assembly, which attaches to a side port on the melting chamber. It contains a non-evaporable getter element (NEG) ⁴³, which is resistively heated to provide continuous gettering action before, during, and after the melting process.

Physical implementation: A commercially available NEG (SAES St172, sintered Zr and Zr-25V-5Fe composite, 35% porosity provides surface area, embedded Mo-wire for resistive heating ⁴⁴) was selected and mounted on a thermocouple tip for temperature control (Fig.5h). Following air exposure events, the NEG element is activated at 800°C under vacuum conditions (i.e., diffuse absorbed oxygen and nitrogen from the surface into the bulk to replenish unsaturated surface ⁴⁴). In continuous operation, the NEG is held at 400°C to purify the process atmosphere by absorbing gaseous impurities on its surface.

c) Loading and Cleaning (Fig.4c):

Conventional: Arc-melting setups are typically built with one melting chamber that contains a fixed melting hearth. The human operator opens the chamber and manually loads feedstock material into the hearth pit. After melting, the operator manually retrieves the material and manually scrubs the hearth pit to restore a clean, uncontaminated surface for the next synthesis cycle.

Automation obstacles: **1)** When the melting chamber is opened, it is exposed to ambient air. After the chamber is closed, a high-purity argon process atmosphere has to be restored in the chamber through multiple cycles of vacuum pumping and argon purging. This typically takes between 1 to 3 hours, represents the most time-consuming step in the conventional synthesis cycle, and thus limits throughput. **2)** Programming a robotic arm to copy how human operators load materials and clean the hearth presents many challenges: How to insert and move the robot inside the constrained chamber space? How to reliably pick, place, and stack small feedstock pieces into the hearth? How to clean the hearth by removing residue effectively? How to implement adequate feedback?

AlloyBot solution: Our system is designed to bypass these obstacles. Firstly, the system features a load-lock chamber, which is connected to the melting chamber by a gate valve. Combined with an automatic transfer mechanism, material can be loaded into the hearth without exposing the melting chamber to ambient air. Thus, the melting process can begin within less than 15 minutes. Secondly, instead of a fixed hearth pit, mobile copper crucibles are employed both as transfer containers and as melting containers. This allows to perform the stacking and cleaning tasks more conveniently outside of the melting chamber. Specifically, feedstock is stacked by the robot into the crucibles at the weighing module (Fig.2f). The crucible and feedstock then form a single handling unit, that is readily transferred by the robot into the load-lock chamber. The transfer mechanism then moves the crucible into the melting chamber, where it vertically inserts into a hearth cavity and functions as melting container. After the melting process, the crucible is contaminated with residue but readily retrieved from the arc-melting system and set aside for later cleaning. Overall, given a supply of 25 clean crucibles, the system can autonomously synthesize 24 alloys in a day, setting aside 1 contaminated crucible per hour. The accumulated 24 contaminated crucibles can then be cleaned by a human assistant once per day (~45 mins manual work) and be resupplied for the next day of operation.

Physical implementation: To illustrate this approach, Fig.5a shows the load-lock chamber with its actuated door open. The robot inserts the crucible down into a loading position inside the chamber (see also Fig.6a). Fig.5b shows the transfer mechanism, which operates like a forklift: It horizontally slides two prongs into slots along the sides of the crucible, then lifts the crucible up vertically, and transfers the crucible horizontally through the open gate valve into the melting chamber. Fig.5c shows the transfer mechanism inserting the crucible vertically into the hearth cavity. Finally, the forklift disengages from the crucible, retracts to the load-lock chamber, the gate valve closes, and the electrodes automatically move into the melting position above the crucible (Fig.5d, Fig.6e). During the melting process illustrated in Figs. 5d to 5g, the conical interface between the hearth cavity and the crucible provides good contact to transport heat and electrical current away from the crucible and into the water-cooled hearth. After melting, the crucible is retrieved from the melting chamber by following the above steps in reverse order.

d) Button Flipping (Fig.4d):

Conventional: To mitigate incomplete melting and mixing after the first melting step, it is common practice to perform multiple additional remelting steps, where the button is first flipped upside-down and then thoroughly remelted, leading to a progressively more uniform composition distribution throughout the material.

Automation obstacle: Button flipping is a cumbersome task, where the electrode tip itself is often used to push the button around the hearth pit until it is successfully tilted up and flipped upside-down. In some cases, the button is accidentally propelled out of the hearth pit and can only be retrieved by opening the chamber.

AlloyBot solution: Mounted onto the same actuator used as transfer mechanism, our system has a scoop which can be vertically raised or lowered. Through combined two-axis motion, this scoop is used to automatically flip the button upside-down between melting steps.

Physical implementation: Fig.5j shows the scoop tilting the button up against the crucible sidewall. Ultimately, the button turns upside-down and slides back to the center of the crucible.

e) Vapor containment (Fig.4e):

Conventional: Elements with a low melting and boiling temperature present a special challenge when heated in combination with higher-melting elements (e.g. Mg with Cu and Y, Al with Ni, Ti with W), requiring high temperatures to fully melt and homogenize the alloy. This often leads to the rapid evaporation of the low-melting elements, which then deposit across the inside wall of the melting chamber.

Automation obstacle: Excessive vapor deposition onto the melting chamber walls can lead to alloy contamination and component failures. In such cases, the operator has to clean the chamber walls, which is difficult to automate. To partially reduce evaporation rates, the community has considered melting under higher pressure atmospheres. For example, an 80% reduction in evaporative mass losses was reported when melting under 20 bar as compared to 1 bar pressure ⁴⁵. While this is in principle attractive, the remaining 20% of deposition would still need to be cleaned off the chamber walls.

AlloyBot solution: As alternative, we have developed an optional vapor containment and exhaust method. The first component is a “vapor containment lid”, which is placed in the load-lock chamber alongside the crucible. In the first step, the automatic transfer mechanism inserts the crucible into the hearth position. In the second step, it places the vapor containment lid on top of the crucible. In the third step, the electrodes automatically insert through the four sideways openings in the lid. Overall, this creates a cavity between the crucible and the lid, where melting can proceed unimpeded because the four electrodes remain stationary. To more effectively contain vapor within this cavity, a “vapor-exhaust crucible” is used as second component. This is a split-type crucible with two lateral exhaust inlets machined into the crucible rim, followed by two internal winding channels leading down to a dedicated bottom vacuum suction port. During the melting process, suction is

applied, such that argon gas flows into the exhaust channels. The argon carries metal vapor with it, which is condensed onto the cool walls of the winding channels. Later, the contaminated lid and crucible are both retrieved from the arc-melting module and set aside for cleaning and reuse during the following day.

Physical implementation: Fig.6b shows the lid placed on top of the vapor-exhaust crucible with the electrodes inserted through the side ports of the lid. Ceramic sheathing is installed along the length of the electrodes as electrical insulator to prevent cross-arcing with the lid. Fig.6c.1 shows the two halves of the vapor-exhaust crucible separated to expose the internal exhaust channels. To demonstrate the effectiveness of this approach, following high-power melting of a $\text{Ti}_{80}\text{Al}_{20}$ button, Fig.6c.2 shows a close-up view where aluminum has deposited inside the exhaust inlet and in diminishing amounts along the length of the channel. Further, Fig.6c.3 shows an inside view of the lid with aluminum deposited on its ceiling and side walls.

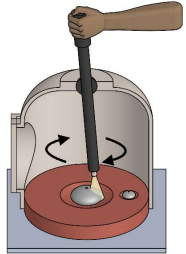
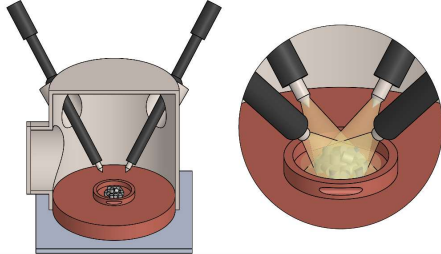
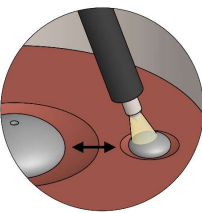
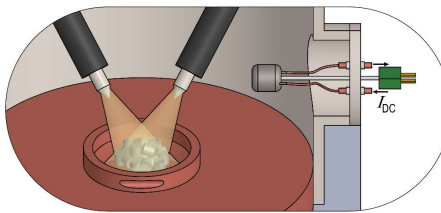
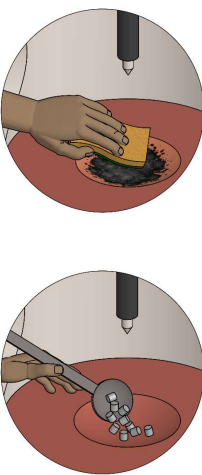
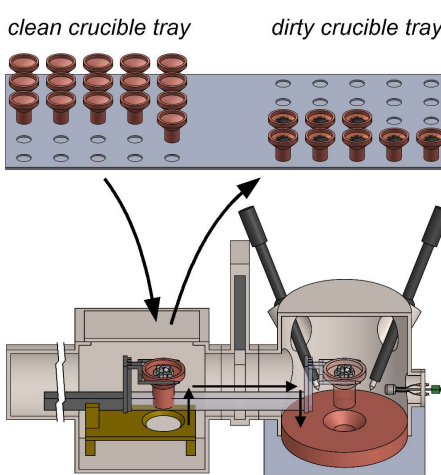
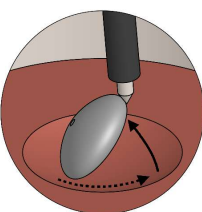
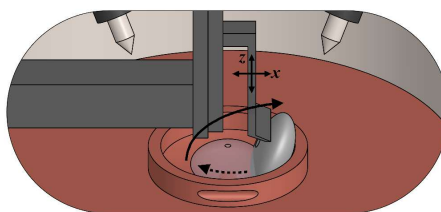
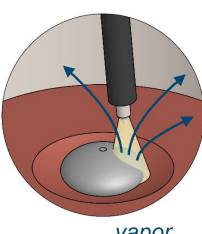
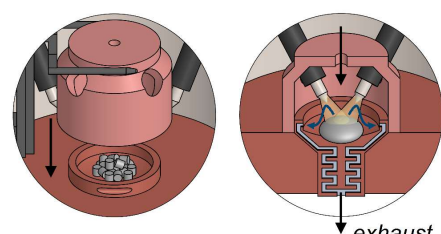
Conventional	AlloyBot
a) Electrodes: Single electrode is manually operated. Heat is localized, so circular motion and feedback are needed for uniform melting. Difficult to automate. 	 Four individually powered electrodes apply heat uniformly from all sides. Eliminates need for actuation and position feedback during melting.
b) Gettering: Operator frequently melts titanium button on the side to getter impurities in Ar gas. Disrupts main process of melting target material. 	 For continuous gettering action and an uninterrupted melting process, an independent non-evaporable getter element is resistively heated.
c) Loading and Cleaning: Chamber is opened and exposed to air. Residue is manually cleaned from hearth. Operator retrieves and loads materials. Time-consuming pump-and-purge cycles are needed to restore clean Ar process atmosphere in the chamber. 	clean crucible tray dirty crucible tray  Reusable copper crucibles serve as containers to move and melt material. Operator cleans crucibles daily. Robot transfers crucible with feedstock into loadlock chamber. Forklift mechanism moves crucible via gate valve into melting chamber, without exposing chamber to air.
d) Flipping: Electrode is used in cumbersome effort to flip button upside down before remelting alloy for homogenization. 	 Transfer mechanism is equipped with a scoop to reliably flip the button through a 2-axis motion.
e) Evaporation: Under excess heat, volatile elements evaporate and deposit onto the chamber walls. Cleaning walls is difficult to automate.  vapor	 exhaust Copper lid is placed over a crucible with internal exhaust channels. Vapor is contained, drawn into these channels, where it deposits onto the cold walls.

Fig.4: Schematic comparison of conventional arc-melting vs. AlloyBot. Various aspects of the conventional arc-melting approach (left) are difficult to automate. The AlloyBot automatic arc-melting module (right) embodies several innovations to simplify automation, make process control robust, and enable high synthesis throughput.

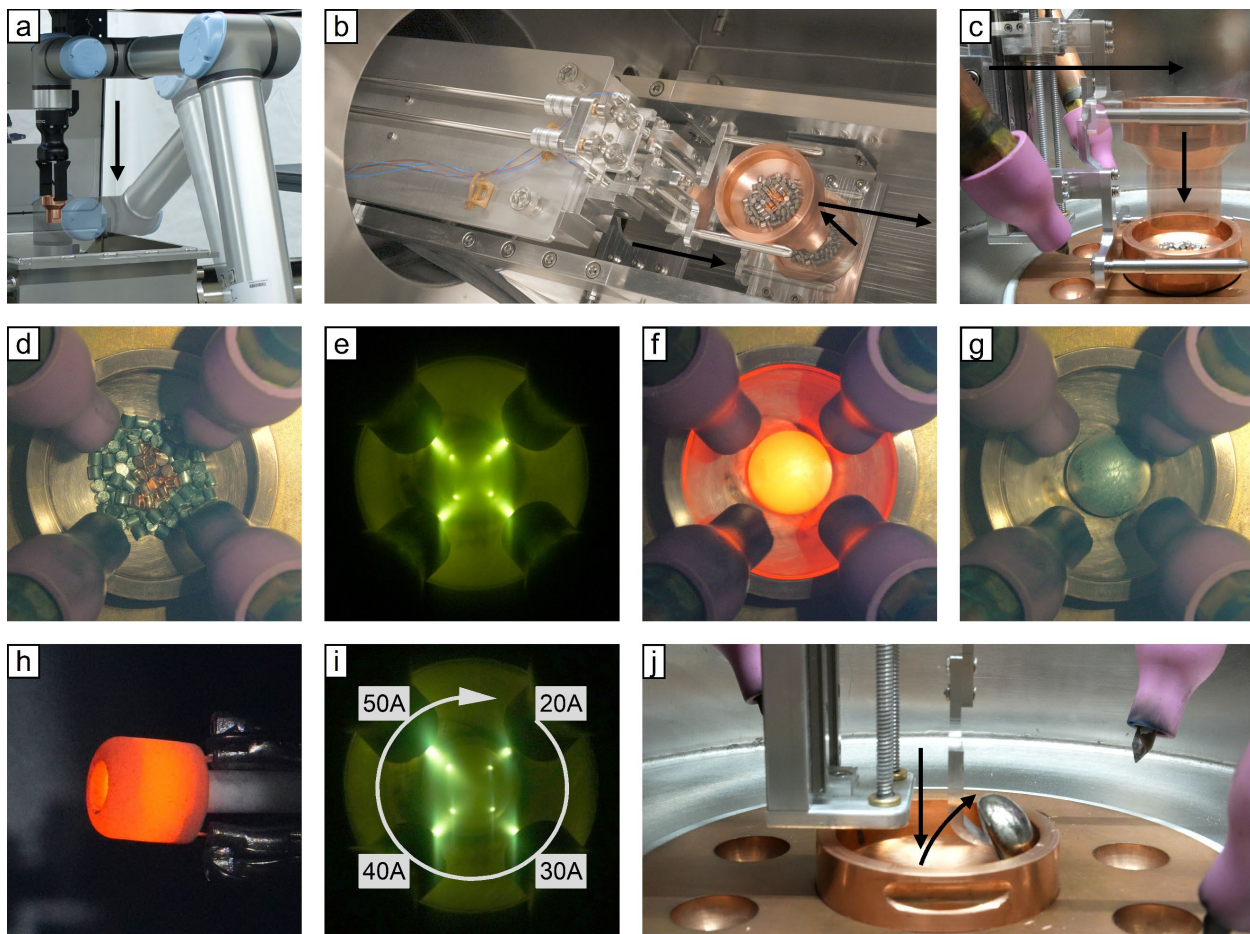


Fig.5: Core features of the automatic arc-melting module. In the loading sequence, **(a)** the door of the load-lock chamber opens, the robot places the copper crucible inside, and the door closes. **(b)** Inside the load-lock chamber, a forklift-style transfer mechanism horizontally drives its prongs into slots along the sides of the crucible, then vertically lifts the crucible up from its loading position, and transfers the crucible horizontally via the open gate valve into the melting chamber, where it **(c)** lowers the crucible into the copper hearth and finally retracts. The gate valve then closes, and the chamber is purged and backfilled with argon. **(d)** At the beginning of the melting sequence, the electrodes move into position above the crucible to a working distance appropriate for the given feedstock quantity. **(e)** The electrodes are energized, form arcs, and heat the feedstock, which naturally melts, merges, and mixes into a single droplet of liquid alloy. **(f)** After the electrodes are deactivated, the alloy solidifies and **(g)** cools down to form an alloy button. Decoupled from the melting process, **(h)** a non-evaporable getter (NEG) element is heated to absorb impurities from the argon atmosphere and prevent their reaction with the alloy. **(i)** Further, the output current from each electrode can be temporally modulated for enhanced stirring (20A base-current with 50A peak-current is circled in clockwise direction here). **(j)** To homogenize the button, it is flipped upside-down and remelted. To this end, the transfer mechanism drives into the melting chamber, lowers a scoop into the crucible, and executes a 2-axis motion to flip the button upside-down.

In combination, these innovations enable a new type of arc-melting system that is readily automated, achieves robust melting results, and can sustain an autonomous synthesis throughput of 1 new alloy per hour. Several additional features supplement the capabilities of the arc-melting module.

Firstly, the approach presented here imposes no fundamental limit on the volume of material that can be synthesized. In its current embodiment, the module is primarily designed to synthesize buttons between 1 to 5 cm³, with the goal to enable alloy testing campaigns across thousands of alloys at a moderate cost. In many cases, however, it will be desirable to produce alloys at a larger volume. For example, after conducting initial property screening across many small-volume alloy buttons, it may be desirable to produce a down-selected subset of these alloys as larger-volume buttons, from which larger mechanical test specimens can then be machined for deeper testing. The small diameter of the basic-type crucible limits the volume of material that can be synthesized. To overcome this, Fig.6d presents a large-diameter-type crucible, which can accommodate a significantly larger volume of material. Indeed, Fig.6d shows a button of Ti-6Al-4V alloy synthesized inside this crucible. The volume of the button is 25 cm³, equivalent to approximately 110 g. (For comparison, due to a higher density, 25 cm³ of Ti₂₀Zr₂₀Hf₂₀Nb₂₀Ta₂₀ alloy would be equivalent to approximately 250 g.) Within our existing arc-melting module, synthesizing alloys significantly beyond 25 cm³ is not realistic given constraints in power, cooling, thermal management, dimensions, etc. In principle, however, future versions of this setup could be scaled up to enable the production of significantly larger ingots.

A second useful feature is the optional suction-casting capability. Fig.6f shows two halves of suction-casting crucibles, exposing the internal cavities, which can be used to cast 2 mm and 4 mm diameter rods, respectively, by applying suction from underneath the crucible. Compared to alloy buttons, where different locations can experience a wide spread of cooling rates, suction-casting has the well-known benefit of imposing comparatively fast cooling rates uniformly along the length of the rod. This typically makes as-cast microstructures more length-scale refined and reproducible. Another practical advantage, especially for automation in self-driving laboratories, is the well-defined rod geometry, which is more easily manipulated than poorly defined, highly variable button geometries. As a practical limitation, however, suction-casting is usually limited to alloys with melting temperatures <1600°C, whereas higher-melting alloys tend to solidify and clog the entrance to the cavity before properly filling the cavity.

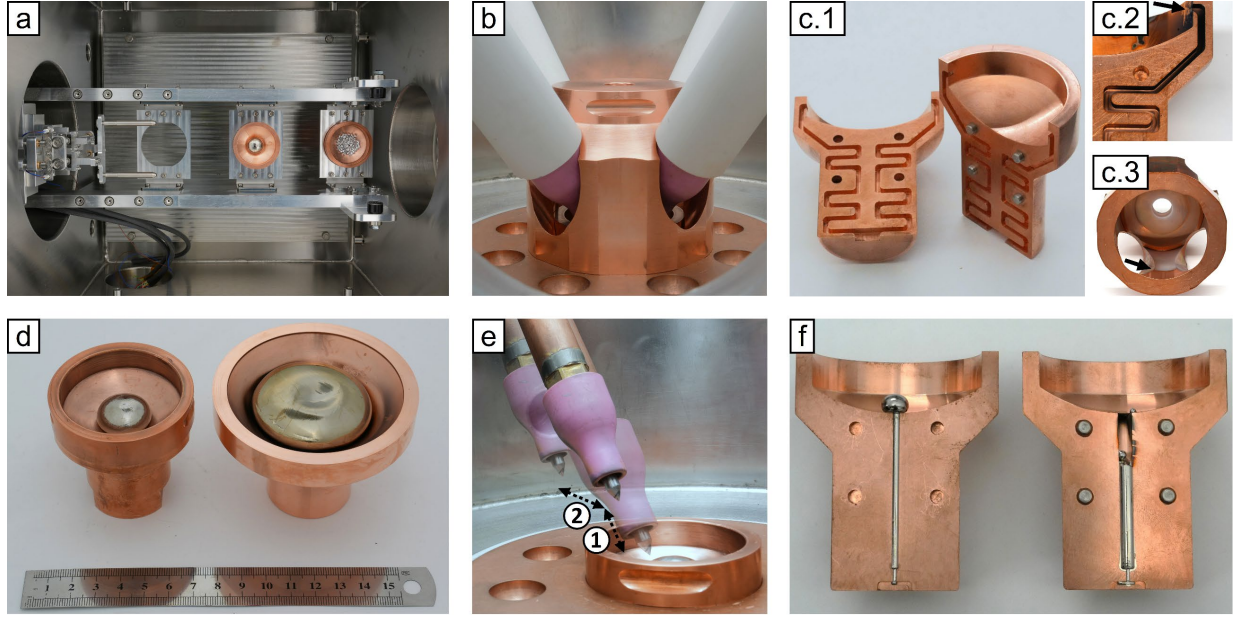


Fig.6: Additional features of the automatic arc-melting module. (a) The load-lock chamber offers three loading positions to accommodate several different crucibles at once, or a lid if needed. (b) Vapor containment lid on top of crucible with electrodes inserted through sideways openings. (c.1) Vapor-exhaust crucible halves separated to expose internal exhaust channel. For validation, a $\text{Ti}_{80}\text{Al}_{20}$ button was repeatedly melted at high power (5 cycles, 2mins each, $4 \times 115\text{A}$ current) and aluminum vapor was effectively contained. (c.2) Close-up view revealing dark aluminum deposit inside the exhaust inlet (indicated by arrow) and in diminishing amounts downwards along the length of the channel. (c.3) Inside-view of the lid showing grey aluminum deposit on the ceiling and exposed sidewalls, whereas the lower sidewall section was shadowed by the crucible rim and remains copper-colored (transition indicated by arrow). (d) Comparison between a basic-type crucible with a 3.4 cm^3 button (left) and a large-diameter-type crucible with a 25 cm^3 Ti-6Al-4V button (right). (e) By default, the electrodes remain stationary during the melting process. Nevertheless, they are actuated for continuous positioning along a two-segment stroke. This allows them to ① insert/retract longitudinally to a variable working distance, and ② retract transversally to provide necessary clearance for crucible transfers. (f) Suction-casting crucible halves with $\text{Zr}_{55}\text{Cu}_{30}\text{Ni}_5\text{Al}_{10}$ rods cast into 2 mm (left) and 4 mm (right) diameter cavities.

2.4 Cycle Timing and Synthesis Throughput

In the overall synthesis process, each alloy undergoes first the weighing operation and second the arc-melting operation. Each operation is completed within a 1-hour cycle time window, and each alloy is therefore completed within a 2-hour total processing time. Meanwhile, the two modules can operate concurrently on two different alloys: While the arc-melting module processes alloy i , the weighing module concurrently processes alloy $i+1$, the next requested composition in the queue. In the steady-state, a synthesis throughput of 1 alloy per hour is thus achieved.

This is illustrated in Fig.7, which shows the sequence of steps concurrently executed at the weighing and arc-melting modules. In this illustration, each step has been allotted more time than required in typical operation. Nevertheless, the full sequence of steps remains well within the 1-hour cycle time limit. The total weighing time is driven by the number of elements and quantity of feedstock that needs to be dispensed and can typically be completed within <0.5 hours. For arc-melting, the total process time comprises steps for pumping/purging, chamber transfers, and (re)melting. Even under generous time allocation, the melting operation typically leaves ≥ 10 min of spare time.

Spare time in the arc-melting process can be spent in idle state, but it can also accommodate optional add-on steps (Fig.7). This is facilitated especially by the fact that the load-lock chamber features not one but three loading positions (Fig.6a), with the benefit that up to three crucibles can be loaded and then sequentially processed within a single 1-hour cycle. To illustrate the utility of this approach, the production of suction-cast rods serves as example: During melting cycle i , a uniform alloy button can be prepared inside a basic-type crucible. Between cycles, the robot can then transfer the alloy button into a suction-casting-type crucible, and place that crucible into loading position 2 (Fig.6a middle position). Next, the robot can place another crucible containing feedstock for the main cycle $i+1$ synthesis into loading position 1 (Fig.6a right position). Finally, during melting cycle $i+1$, the main synthesis of alloy $i+1$ is completed first. Second, the available spare time can be used to complete the suction casting step for alloy i . While this step adds 1 hour to the total production time of alloy i , completing suction-casting during the spare time of subsequent cycle $i+1$ ensures that an effective throughput of 1 alloy per hour can be maintained.

A similar strategy can be employed when alloys need to be melted in separate stages. For example, in the synthesis of $\text{Ti}_{20}\text{Zr}_{20}\text{Hf}_{20}\text{Nb}_{20}\text{Ta}_{20}$ alloy, the high melting temperature of Ta can pose an obstacle. Synthesis becomes more straightforward in two stages: First, a $\text{Nb}_{20}\text{Ta}_{20}$ precursor button with a lower melting temperature can be prepared during the spare time of cycle i . Next, in cycle $i+1$ the precursor button is more readily mixed and homogenized with the remaining Ti_{20} , Zr_{20} , and Hf_{20} elemental feedstock.

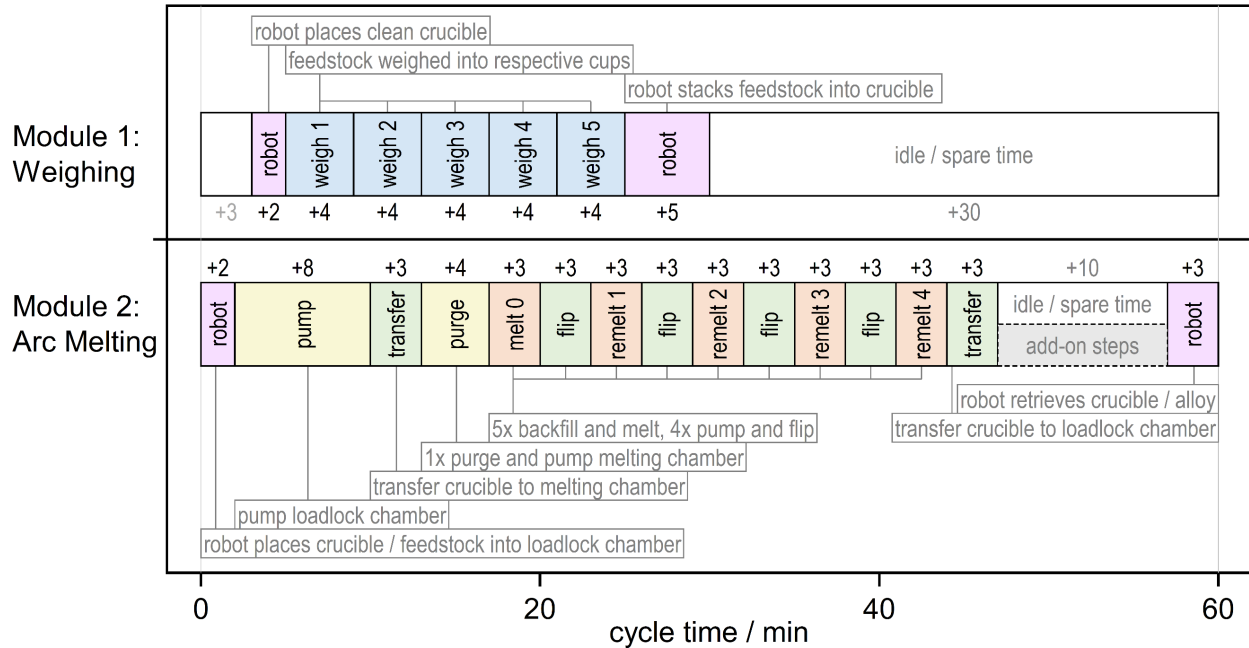


Fig.7. Sequence of steps during weighing and arc-melting operation. Each operation can be readily completed within the allotted 1h cycle time window. In the arc-melting operation, spare time can be used to accommodate add-on steps such as suction casting or the synthesis of precursor alloy. By operating the weighing module and the arc-melting module concurrently, an effective synthesis throughput of 1 alloy per hour is achieved.

2.5 Alloy Synthesis and Validation

Three alloys were synthesized to validate the capabilities of the arc-melting module. Fig.8 shows back-scatter electron micrographs and X-ray diffractograms (XRD) for the as-synthesized alloy microstructures.

The first alloy is Ti-6Al-4V (Fig.8a), selected to represent conventional single-principal element alloys and demonstrate impurity control despite a strong oxygen affinity. The observed microstructure is typical of as-solidified Ti-6Al-4V ⁴⁶, with V-rich beta phase ribs (bright) retained between Al-rich alpha phase laths (dark). The diffractogram clearly shows the HCP alpha phase, whereas the BCC beta phase cannot be distinguished due to its low volume fraction and overlapping peaks.

The second alloy is Ti₂₀Zr₂₀Hf₂₀Nb₂₀Ta₂₀ (Fig.8b), also known as Senkov alloy, selected here to represent refractory multi-principal element alloys and especially the challenge of alloying high-melting elements such as Ta. In line with the literature ^{47,48}, the observed microstructure exhibits colonies of Nb and Ta-rich dendrites (bright), segregation of Ti, Zr, and Hf to the interdendritic region (dark), and a single-phase BCC diffractogram.

The third alloy is Zr₅₅Cu₃₀Ni₅Al₁₀ (Fig.8c), selected to represent bulk glass forming alloys and serve as benchmark for melt-quenching by suction-casting. In the first step, a slow-cooled alloy button was prepared. In the second step, pieces from this button were suction-cast into rods of 4 mm and

2 mm diameter to form a glass (Fig.6f, cooling rates ~ 60 and 250 K/sec, respectively ⁴⁹). The slow-cooled button exhibits a complex crystalline microstructure, with $\text{Al}_5\text{Ni}_3\text{Zr}_2$ intermetallic dendrites ^{50,51} formed first upon solidification, followed by additional interdendritic phases. By contrast, XRD on the 4 mm and 2 mm cast rods reveals the formation of a glassy phase. However, a small fraction of $\text{Al}_5\text{Ni}_3\text{Zr}_2$ intermetallic is still detected. Indeed, the micrograph for the 2 mm specimen reveals incipient $\text{Al}_5\text{Ni}_3\text{Zr}_2$ dendrites dispersed within the glassy matrix. Overall, these observations suggest that the arc-melting module is in principle capable of synthesizing bulk metallic glasses. However, partial crystallization is observed, which we attribute to the high oxygen content in the Zr pellet feedstock (grade 702, certified at 1400 ppmw), which has been shown to reduce glass forming ability by promoting the formation of $\text{Al}_5\text{Ni}_3\text{Zr}_2$ ⁵².

Overall, all three alloys are compositionally uniform, their microstructures align with similar reports in the literature, are free of major defects, and exhibit no evidence of undesired phases such as oxides, nitrides, or carbides, especially at boundaries.

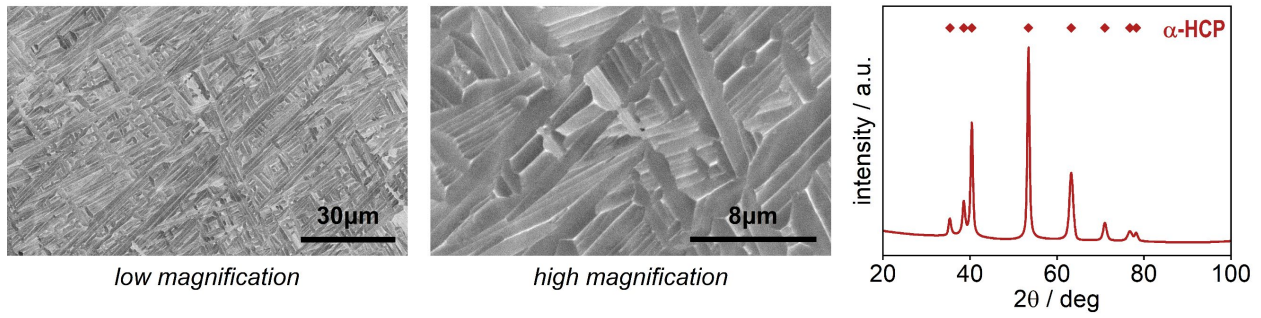
Elemental analysis results are summarized in Table 2. Within a ± 1 at.% measurement uncertainty typical of energy dispersive X-ray spectroscopy (EDX), the concentrations of all metallic constituents in the as-synthesized alloys match the target concentrations weighed in prior to melting. Notably, no significant evaporative losses are detected for Al. One hypothesis could attribute this to more uniform heating provided by the four electrodes, leading to more moderate local excess temperatures and reduced evaporation. Future work will systematically quantify compositions and model evaporative losses for optimal composition accuracy.

Finally, the interstitial impurity concentrations (carbon, nitrogen, oxygen) reported in Table 2 fall well within the range typical of arc-melted alloys ⁵³. A preliminary comparison to impurity concentrations in the feedstock materials suggests that the melting process does not appreciably add carbon and oxygen impurities to the alloy. Overall, this indicates that the reusable clean copper crucibles, fast load-lock transfers, and NEG argon purification embodied in the arc-melting module are effective measures to support the synthesis of high-purity, high-quality alloys.

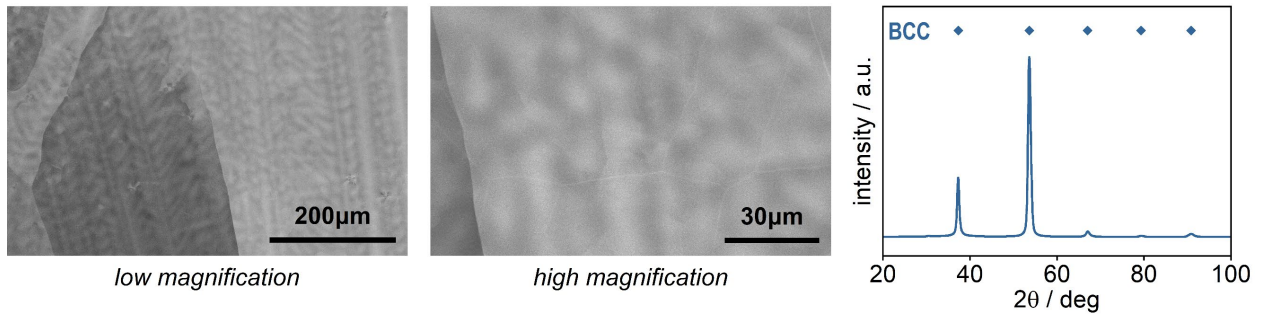
Table 2. Elemental analysis of demo alloys. For metallic constituents, the concentrations weighed in prior to melting are compared to the concentrations measured by EDX after melting, and found to match within a typical measurement uncertainty ± 1 at.%. While small excess quantities of Al were weighed in to compensate for anticipated evaporative losses, no significant losses of Al are observed. To generate a similar benchmark for interstitial impurities, the concentrations of carbon, nitrogen, and oxygen weighed in as feedstock impurities were calculated based on the chemical certification sheets available for each feedstock material (see Supplementary Table S2). These “certified” impurity estimates are lower than the impurity concentrations measured by two independent testing services for the arc-melted alloys. But they may significantly underestimate true feedstock impurity levels, as illustrated by the example of Ti feedstock pellets, which were tested to reveal higher carbon and oxygen concentrations than certified. Using these measured Ti feedstock impurity values, “Ti-revised” estimates were calculated for each alloy and found to match the measured alloy impurity concentrations more closely. Similarly, all other feedstock materials may be contributing higher impurity concentrations than certified, which could explain increased nitrogen concentrations in the alloys, but testing all feedstock is beyond scope here. Overall, these observations suggest that impurities may not primarily be introduced by the melting process, but more likely as pre-existing feedstock impurities. The impurity levels measured for each alloy are typical of arc-melted alloys⁵³, validating the performance of the arc-melting module.

Ti-6Al-4V	Ti /wt.%	Al /wt.%	V /wt.%			Impurities	C /ppmw	N /ppmw	O /ppmw
weighed in	89.5	6.5	4.0			certified:	10	12	220
						Ti-revised:	64	<46	673
measured	89.7	6.4	3.9			service 1:	100	580	730
						service 2:	90	310	810
Ti₂₀Zr₂₀Hf₂₀Nb₂₀Ta₂₀	Ti /at.%	Zr /at.%	Hf /at.%	Nb /at.%	Ta /at.%	Impurities	C /ppmw	N /ppmw	O /ppmw
weighed in	20.0	20.0	20.0	20.0	20.0	certified:	28	27	324
						Ti-revised:	33	<30	365
measured	20.4	19.3	20.1	20.0	20.2	service 1:	70	140	540
						service 2:	80	170	260
Zr₅₅Cu₃₀Ni₅Al₁₀	Zr /at.%	Cu /at.%	Al /at.%	Ni /at.%		Impurities	C /ppmw	N /ppmw	O /ppmw
weighed in	55.0	30.0	10.5	5.0		certified:	67	31	938
measured	54.2	30.3	10.9	5.2		service 1:	<5	660	1010
Ti Pellet Feedstock						Impurities	C /ppmw	N /ppmw	O /ppmw
certified						certified:	10	11	240
measured						service 1:	70	<50	750

a) Ti-6Al-4V



b) $\text{Ti}_{20}\text{Zr}_{20}\text{Hf}_{20}\text{Nb}_{20}\text{Ta}_{20}$



c) $\text{Zr}_{55}\text{Cu}_{30}\text{Ni}_5\text{Al}_{10}$

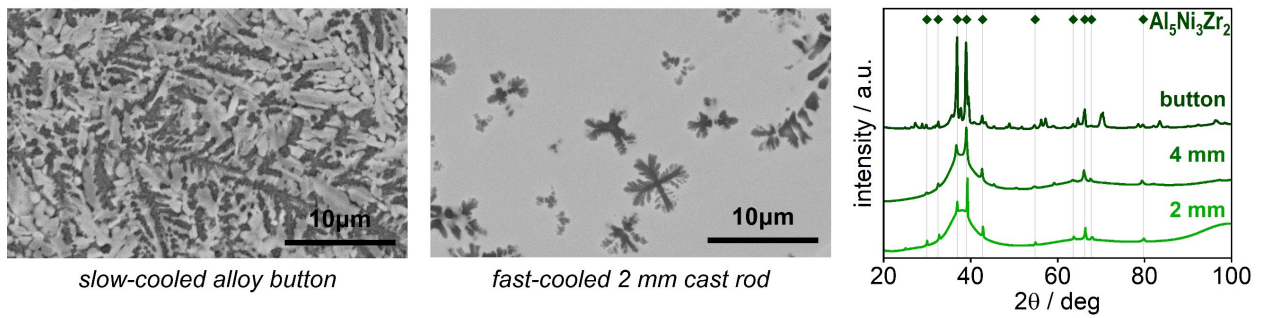


Fig.8. Electron micrographs and X-ray diffractograms for three as-synthesized demo alloys, including (a) Ti-6Al-4V, (b) $\text{Ti}_{20}\text{Zr}_{20}\text{Hf}_{20}\text{Nb}_{20}\text{Ta}_{20}$, (c) $\text{Zr}_{55}\text{Cu}_{30}\text{Ni}_5\text{Al}_{10}$.

3. Discussion

By combining the design innovations and process automation described above, our AlloyBot arc-melting system achieves the performance objectives defined in Table 1, placing it at the forefront of automatic alloy synthesis methods for autonomous, self-driving laboratories.

The benefits are clear: A human researcher working full-time on conventional, manual alloy testing could, by a generous estimate, synthesize, heat-treat, and characterize 1 alloy per week. By contrast, the first AlloyBot building block presented here can synthesize over 150 alloys per week, which represents an acceleration by over 100×. Only about 5 hours of human assistance are needed for maintenance per week, which can significantly lower the unit cost per alloy. Further, AlloyBot achieves the same gold-standard specimen quality and, unlike intuition-guided manual melting, more reproducible results because all process parameters can be precisely controlled and monitored.

Automatic arc-melting also stands out in comparison to alternative high-throughput alloy synthesis strategies, which historically sacrifice quality in favor of throughput. As a first example, diffusion couples have been used to produce compositionally graded bulk libraries, which can arguably represent about 10 distinct compositions across a junction. This has proven useful to determine phase equilibria, evaluate diffusion kinetics, and for preliminary property screening^{54–57}. Drawbacks, however, include long interdiffusion times, and that large uniform specimens cannot usually be extracted. As a second example, combinatorial thin-film deposition has been used to produce compositionally graded thin-film libraries containing hundreds of compositions. Due to cooling rates on the order of 10^9 K/sec, this approach excels at studying the formation and properties of metastable alloys^{12,18,26,39,58–64}, but conversely struggles with realizing equilibrium states. Further, with a typical film thickness on the order of micrometers, microstructure evolution is length-scale constrained, and the determination of bulk-representative structural properties is not usually possible. More generally, both methods rely on compositionally graded libraries to achieve high throughput. Compositions probed by a single library therefore form a tight cluster in composition space. To probe composition domains more independently, many libraries need to be prepared in a lower throughput manner. Automatic arc-melting can clearly excel here: Every single alloy can probe an entirely independent composition with constituents from all across the periodic table^{27,65}. Alloys can be produced in bulk form, at a reasonable cost (Fig.3), and in significant volumes (Fig.6d), to enable processing-structure-property assessments which use the same gold-standard methods already established in conventional metallurgy.

The leading alternative to automatic arc-melting is, arguably, high-throughput alloy synthesis by additive manufacturing^{66–73}. Such approaches typically feed, mix, and fuse powder feedstock of different elements at controlled rates, to 3D-print bulk specimens at desired target compositions. At present, such setups can typically synthesize about 100 specimens per week at a volume around 1 cm³ each. Compared to automatic arc-melting, additive approaches have compelling benefits: Specimens can be produced in the desired net geometry, e.g., as tensile specimens⁷⁴. Higher cooling rates (10^3 to 10^5 K/sec) can allow to blend even challenging element combinations (e.g. significant segregation or melting temperature difference) into finer-scale microstructures. Finally, as-printed specimens can directly represent processing conditions relevant for additive manufacturing. At the same time there are drawbacks compared to automatic arc-melting: Powder feedstock is often more expensive than bulk feedstock, and can absorb significantly higher impurity concentrations. Especially in new

compositions, controlling the printing process to manage defects and crystallographic texture is not trivial. Also, alloys prepared by arc-melting, casting, and lab-scale thermo-mechanical processing are overall more suitable to represent traditional alloy manufacturing and processing pathways. Altogether, we propose that automatic arc-melting and additive manufacturing each have unique and complementary strengths. We anticipate that both methods will continue to evolve in parallel and be adopted in tandem for autonomous alloy development laboratories.

In conclusion, the automatic arc-melting synthesis capability introduced here overcomes a critical barrier on the road towards autonomous, self-driving laboratories. While our primary focus lies on structural alloys for extreme operating conditions, arc-melting synthesis is also broadly used to develop alloys and inorganic compounds for functional applications. The high-throughput, high-quality, low-cost, and large-volume synthesis performance of this platform can therefore enable rapid testing campaigns across thousands of materials and various application areas.

In future work, we will show how this system can be transformed into an intelligent synthesis platform – what we refer to as “SmartMelting”. This is based on a simple premise: Unlike conventional arc-melting guided by human intuition, the AlloyBot arc-melting approach is ideally suited to achieve superior process control. Process parameters such as the electrode working distance, power output, and duration can be precisely controlled and monitored. Given the unobstructed top-view, the melting process can be monitored in real-time using optical methods such as imaging and pyrometry. Various additional in-situ sensing methods can provide real-time feedback to adjust process parameters and ensure synthesis quality. Feedback from ex-situ characterization can be used to systematically learn and predict what process parameters lead to optimal synthesis results. For example: For a new target composition, how should the electrode working distance, output power and duration, number of remelting cycles, and feedstock input masses be set, to reliably achieve uniform melting and mixing balanced with minimal porosity, solidification shrinkage, evaporation, compositional deviations, impurity pickup, and micro-segregation? Our arc-melting system is already configured to stream process data and metadata, setting the foundation to develop SmartMelting in the next step.

Finally, as part of our larger AlloyBot autonomous laboratory, the synthesis modules introduced here will be seamlessly integrated with various other modules for specimen preparation, thermo-mechanical processing, microstructure characterization, property testing, high-throughput modeling, and artificial intelligence, all combined to accelerate alloy development by over 100×.

4. Methods

The automatic synthesis system presented here was built and developed by the authors from the ground up. It incorporates various components – some available off-the-shelf, some custom-manufactured to specification, and some manufactured in-house by the authors – including especially the following major items: The six-axis robot is a UR10e cobot (Universal Robots A/S), which is mounted on a custom-manufactured 8-meter stroke length linear actuator (Festo SE & Co. KG). The authors designed and assembled the full weighing module, including subassemblies such as the pellet and wire dispensers (various parts machined to order by Xometry, Inc.) and the power, electronics, and pneumatics panel. The arc-melting chamber (support frame, chamber, electrode assemblies, hearth, cooling water manifold) was manufactured by MTI Corporation, starting from their preexisting AM-400 model, incorporating various custom modifications requested by the authors (e.g., modified hearth design for suction-casting, modified chamber layout), and using TIG welding power supplies to power the electrodes (Everlast 250EX). The load-lock chamber was custom-manufactured by the Kurt J. Lesker Company and connected to the melting chamber via a gate valve (VAT Group AG). The authors designed and assembled all remaining sub-assemblies such as the support frame, load-lock actuation, crucible transfer mechanism, electrode retraction mechanism, the vacuum and gas system, the power, electronics, and pneumatics panel, and more. The authors further designed and manufactured all copper crucible types and the vapor containment lid in-house. Both the weighing and arc-melting module are controlled and integrated by the authors using programmable logic controllers (PLCs), human-machine interfaces (HMIs), and an industrial PC (all from B&R Industrial Automation GmbH). Altogether, this enables the system to read all sensor signals, control all actuation, communicate between modules, and execute the programmed synthesis protocols such that alloys can be automatically synthesized as described above.

As feedstock, pellets (cylindrical geometry 3.175 mm diameter and length, sourced as evaporation materials) and wire (diameter between 0.5 to 1.0 mm) was used, with vendors and purities listed in supplementary Table S3. St172 was used as NEG material (HI/7.5-7 from SAES Getters/U.S.A. Inc.)⁴⁴. Following synthesis, alloys were sectioned using wire electric discharge machining (Makino UX3), mechanically ground to 1200 grit SiC finish, and further polished using ion milling (TechnoorgLinda SEM-Prep-Smart). X-ray diffractograms were recorded using a Rigaku MiniFlex XPC diffractometer. Back-scatter electron images were recorded using a Zeiss GeminiSEM 300 scanning electron microscope, along with metallic constituent concentrations quantified using an Oxford Instruments Ultim Max 100 EDX detector. Impurity concentrations reported in Table 2 were determined by two independent testing services using inert gas fusion for oxygen and nitrogen quantification and combustion analysis for carbon quantification (service 1: Luvak Inc., certified to ASTM E 1409-13 and ASTM E 1941-16; service 2: Anderson Laboratories Inc., certified to ASTM E 1019).

Some images in this article were edited using Adobe Photoshop 2026 (e.g. overlaying and blending to indicate motion ranges, image stitching, erasing of brand logos and trademarks, background corrections) to illustrate the operation of the system more effectively, while faithfully representing the system.

Acknowledgement

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0001933. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. The authors further gratefully acknowledge generous support from the Wisconsin Alumni Research Foundation (WARF). The authors also gratefully acknowledge generous in-kind support from B&R Industrial Automation. Aubrey Ugurowsky contributed to photography and videography presented herein. Finally, the authors are grateful for support from and insightful discussions with various colleagues and partners, especially including Jan Schroers, Sungwoo Sohn, Dan Miracle, Tresa Pollock, Dan Thoma, John Perepezko, Paul Voyles, Izabela Szlufarska, Hyunseok Oh, Adrien Couet, Bhagwat Ghule, Nate Eklof, Zack Rielley, Mark Nornberg, Chris Kailhofer, Nick Bulloss, Jeff Elsner, John Fernsler, Pete Nemmetz, Stephanie Whitehorse, Chengyi Wu, Doug Childers, Matt Kelley, John Steinberg, Oskar Schnippering, Alex Curran, Maxwell Alexander, Laurent Pilon, Pankaj Trivedi, Emily Kinser, Saryu Fensin, Carolina Frey, Noah Philips, Scott Oppenheimer, Punnathat Bordeenithikasem, Haihan Sun, and Maxwell Shinn.

Author contributions

S.A.K. developed the original research plan, managed funding, and supervised this work. V.S. and P.B. completed the primary design, manufacturing, assembly, and integration work. V.S. and M.E.P. conducted the melting tests. All authors contributed to data analysis and the preparation of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version of this article contains a supplementary document, and supplementary video files illustrating the operation of this system.

References

1. Darolia, R. Development of strong, oxidation and corrosion resistant nickel-based superalloys: critical review of challenges, progress and prospects. *International Materials Reviews* **64**, 355–380 (2019).
2. Perepezko, J. H. The hotter the engine, the better. *Science* (1979). **326**, 1068–1069 (2009).
3. Pollock, T. M. Alloy design for aircraft engines. *Nat. Mater.* **15**, 809–815 (2016).
4. Teasley, T. NASA's Rotating Detonation Rocket Engine Development. Preprint at (2025).
5. Teasley, T., Fedotowsky, T., Gradl, P., Austin, B. & Heister, S. Current State of NASA Continuously Rotating Detonation Cycle Engine Development. *AIAA SciTech Forum and Exposition, 2023* <https://doi.org/10.2514/6.2023-1873> (2023) doi:10.2514/6.2023-1873.
6. Peters, A. B. *et al.* Materials design for hypersonics. *Nature Communications* **2024 15:1** **15**, 3328- (2024).
7. Zinkle, S. J. & Busby, J. T. Structural materials for fission & fusion energy. *Materials Today* **12**, 12–19 (2009).
8. Hatler, C. *et al.* The path towards plasma facing components: A review of state-of-the-art in W-based refractory high-entropy alloys. *Curr. Opin. Solid State Mater. Sci.* **34**, 101201 (2025).
9. Cladouhos, T. T. & Callahan, O. A. Heat Extraction from SuperHot Rock-Technology Development.
10. Miracle, D. B. & Senkov, O. N. A critical review of high entropy alloys and related concepts. *Acta Mater.* **122**, 448–511 (2017).
11. Senkov, O. N., Miracle, D. B., Chaput, K. J. & Couzinie, J.-P. Development and exploration of refractory high entropy alloys—A review. *J. Mater. Res.* 1–37 (2018).
12. Kube, S. A. *et al.* Phase selection motifs in High Entropy Alloys revealed through combinatorial methods: Large atomic size difference favors BCC over FCC. *Acta Mater.* **166**, 677–686 (2019).
13. Chen, S., Tong, Y. & Liaw, P. K. Additive Manufacturing of High-Entropy Alloys: A Review. *Entropy* **2018, Vol. 20**, **20**, (2018).
14. Islam, Z. *et al.* Reactive Synthesis in Additive Manufacturing of an Ultrahigh Temperature MoSiB Alloy. *JOM* **2023 75:12** **75**, 5037–5045 (2023).
15. Frey, C. *et al.* A Perspective on the Historical and Contemporary Development of Refractory Alloys. *Metallurgical and Materials Transactions A* **2025 57:2** **57**, 461–503 (2025).
16. Mullin, K. M., Kube, S. A., Wu, S. K. & Pollock, T. M. Cracking and Precipitation Behavior of Refractory BCC–B2 Alloys Under Laser Melting Conditions. *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.* **55**, 3809–3823 (2024).
17. Demetriou, M. D. *et al.* A damage-tolerant glass. *Nat. Mater.* **10**, 123 (2011).
18. Kube, S. A. & Schroers, J. Metastability in high entropy alloys. *Scr. Mater.* **186**, 392–400 (2020).
19. Wei, S., He, F. & Tasan, C. C. Metastability in high-entropy alloys: A review. *J. Mater. Res.* **33**, 2924–2937 (2018).
20. DelVecchio, E. *et al.* Metastable cellular structures govern localized corrosion damage development in additive manufactured stainless steel. *npj Materials Degradation* **2024 8:1** **8**, 45- (2024).
21. Kube, S. A. *et al.* Navigating the BCC–B2 refractory alloy space: Stability and thermal processing with Ru–B2 precipitates. *Acta Mater.* **265**, 119628 (2024).
22. Ren, J. *et al.* Strong yet ductile nanolamellar high-entropy alloys by additive manufacturing. *Nature* **2022 608:7921** **608**, 62–68 (2022).
23. Huang, L. J., Geng, L. & Peng, H. X. Microstructurally inhomogeneous composites: Is a homogeneous reinforcement distribution optimal? *Prog. Mater. Sci.* **71**, 93–168 (2015).
24. Wat, A. *et al.* Bioinspired nacre-like alumina with a bulk-metallic glass-forming alloy as a compliant phase. *Nature Communications* **2019 10:1** **10**, 961- (2019).

25. Chookajorn, T., Murdoch, H. A. & Schuh, C. A. Design of stable nanocrystalline alloys. *Science* (1979). **337**, 951–954 (2012).
26. Kube, S. A. *et al.* Combinatorial study of thermal stability in ternary nanocrystalline alloys. *Acta Mater.* **188**, 40–48 (2020).
27. Miracle, D. B. & Thoma, D. J. Autonomous research and development of structural materials – An introduction and vision. *Curr. Opin. Solid State Mater. Sci.* **33**, 101188 (2024).
28. Xu, P. *et al.* Revealing relationships between composition, microstructure, and mechanical property of molybdenum alloys via high-throughput experiments. *J. Alloys Compd.* **1057**, 186662 (2026).
29. Liu, Y., Wang, J., Xiao, B. & Shu, J. Accelerated development of hard high-entropy alloys with data-driven high-throughput experiments. *J Mater Inf* 2022;2:3. **2**, N/A-N/A (2022).
30. Ouyang, G. *et al.* Design of refractory multi-principal-element alloys for high-temperature applications. *npj Computational Materials* 2023 9:1 **9**, 141- (2023).
31. 32-Station (20g) Automatic Arc Melting System for High Throughput Allo – MTI Online Store. <https://mtixtl.com/products/sp-msm360>.
32. Automated Arc Melting System up to 36 Samples for Materials Research a – MTI Online Store. <https://mtixtl.com/products/am-msm-36>.
33. Yokoyama, Y. Development of an Automatic Fabrication System for Cast Glassy Alloys. *Metallurgical and Materials Transactions B* 2015 46:2 **46**, 893–905 (2015).
34. Warren, J. A. *et al.* Overcoming Roadblocks for Implementing AI/ML Methods for Materials Advancement. *Annu. Rev. Mater. Res.* <https://doi.org/10.1146/ANNUREV-MATSCI-072924-102951> (2026) doi:10.1146/ANNUREV-MATSCI-072924-102951.
35. Szymanski, N. J. *et al.* Toward autonomous design and synthesis of novel inorganic materials. *Mater. Horiz.* **8**, 2169–2198 (2021).
36. Review of low-cost self-driving laboratories in chemistry and materials science: the “frugal twin” concept - Digital Discovery (RSC Publishing) DOI:10.1039/D3DD00223C. <https://pubs.rsc.org/en/content/articlehtml/2024/dd/d3dd00223c>.
37. Fensin, S. & Wanni, J. Systems and Methods For Automated and Autonomous Arc Melting (provisional patent S-195376.000, filed 2025). (2025).
38. Kube, S. A. Arc Melting Apparatus and Approach (patent pending, filed 07/22/2025).
39. Kube, S. A. *et al.* Compositional dependence of the fragility in metallic glass forming liquids. *Nat. Commun.* **13**, 3708 (2022).
40. Ward, L. *et al.* A machine learning approach for engineering bulk metallic glass alloys. *Acta Mater.* **159**, 102–111 (2018).
41. Miracle, D. B., Louzguine-Luzgin, D. V, Louzguina-Luzgina, L. V & Inoue, A. An assessment of binary metallic glasses: correlations between structure, glass forming ability and stability. *International Materials Reviews* **55**, 218–256 (2010).
42. Schmehr, J. L. & Wilson, S. D. Active Crystal Growth Techniques for Quantum Materials. *Annu. Rev. Mater. Res.* **47**, 153–174 (2017).
43. Getter pump with high gas sorption velocity. (1998).
44. SAES Getters. St 171 ® and St 172-Sintered Porous Getters. https://www.saesgetters.com/industrial-getters-dispensers/wp-content/uploads/sites/9/2024/02/St-171-172_Sintered-Porous-Getters_1.pdf.
45. Bradshaw, A. R. & Fort, D. A laboratory-scale arc furnace for melting volatile metals under elevated inert gas pressures. *Review of Scientific Instruments* **63**, 5459–5463 (1992).

46. Stefanescu, D. M. & Ruxanda, R. Solidification Structures of Titanium Alloys. *Metallography and Microstructures* 116–126 (2004) doi:10.31399/ASM.HB.V09.A0003728.
47. Senkov, O. N., Scott, J. M., Senkova, S. V., Miracle, D. B. & Woodward, C. F. Microstructure and room temperature properties of a high-entropy TaNbHfZrTi alloy. *J. Alloys Compd.* **509**, 6043–6048 (2011).
48. Dirras, G. *et al.* Mechanical behavior and microstructure of Ti₂₀Hf₂₀Zr₂₀Ta₂₀Nb₂₀ high-entropy alloy loaded under quasi-static and dynamic compression conditions. *Mater. Charact.* **111**, 106–113 (2016).
49. Lin, X. H. & Johnson, W. L. Formation of Ti–Zr–Cu–Ni bulk metallic glasses. *J. Appl. Phys.* **78**, 6514–6519 (1995).
50. Seki, I., Wakoh, K., Kawashima, A., Kimura, H. & Inoue, A. Preparation of a Wide Zr 55 Al 10 Ni 5 Cu 30 Metallic Glass Sheet by a Twin-Roller Type Casting Method and Its Mechanical Properties. <https://doi.org/10.2320/matertrans.47.1926> (1209) doi:10.2320/matertrans.47.1926.
51. Sergiienko, R. A., Shcheretskyi, O. A., Zadorozhnyy, V. Y., Verkhovliuk, A. M. & Louzguine-Luzgin, D. V. Investigation of Zr₅₅Cu₃₀Al₁₀Ni₅ bulk amorphous alloy crystallization. *J. Alloys Compd.* **791**, 477–482 (2019).
52. Liu, Y. *et al.* The effect of impurities in zirconium on the formation and mechanical properties of Zr₅₅Cu₃₀Al₁₀Ni₅ metallic glass. *J. Non. Cryst. Solids* **596**, 121878 (2022).
53. Belcher, C. H., Lavernia, E. J. & Apelian, D. The Influence of Interstitial Impurities on the Design and Processing of Refractory Complex Concentrated Alloys. *ProQuest Dissertations and Theses* (United States -- California, 2024).
54. Kodentsov, A. A., Bastin, G. F. & Van Loo, F. J. J. The diffusion couple technique in phase diagram determination. *J. Alloys Compd.* **320**, 207–217 (2001).
55. Zhao, J. C., Zheng, X. & Cahill, D. G. High-throughput diffusion multiples. *Materials Today* **8**, 28–37 (2005).
56. Campbell, C. E., Zhao, J. C. & Henry, M. F. Comparison of experimental and simulated multicomponent Ni-base superalloy diffusion couples. *Journal of Phase Equilibria and Diffusion* 2004 25:1 **25**, 6–15 (2004).
57. Coury, F. G., Wilson, P., Clarke, K. D., Kaufman, M. J. & Clarke, A. J. High-throughput solid solution strengthening characterization in high entropy alloys. *Acta Mater.* **167**, 1–11 (2019).
58. Bordeenithikasem, P. *et al.* Determination of critical cooling rates in metallic glass forming alloy libraries through laser spike annealing. *Sci. Rep.* **7**, (2017).
59. Wolf, W. *et al.* Formation and stability of complex metallic phases including quasicrystals explored through combinatorial methods. *Sci. Rep.* **9**, 7136 (2019).
60. Eckert, H. *et al.* Soliquidity: a descriptor for atomic geometrical confusion. *npj Computational Materials* (accepted for publication) (2025).
61. Li, M. X. *et al.* Data-driven discovery of a universal indicator for metallic glass forming ability. *Nature Materials* 2021 21:2 **21**, 165–172 (2021).
62. Gregoire, J. M. *et al.* High-throughput synchrotron X-ray diffraction for combinatorial phase mapping. *urn:issn:1600-5775* **21**, 1262–1268 (2014).
63. Takeuchi, I. *et al.* Identification of novel compositions of ferromagnetic shape-memory alloys using composition spreads. *Nature Materials* 2003 2:3 **2**, 180–184 (2003).
64. Ludwig, A. Discovery of new materials using combinatorial synthesis and high-throughput characterization of thin-film materials libraries combined with computational methods. *npj Computational Materials* 2019 5:1 **5**, 70– (2019).
65. Miracle, D. B., Li, M., Zhang, Z., Mishra, R. & Flores, K. M. Emerging Capabilities for the High-Throughput Characterization of Structural Materials. *Annu. Rev. Mater. Res.* **51**, 131–164 (2021).
66. Moorehead, M. *et al.* High-throughput synthesis of Mo-Nb-Ta-W high-entropy alloys via additive manufacturing. *Mater. Des.* **187**, 108358 (2020).
67. Nelaturu, P. *et al.* Multi-principal element alloy discovery using directed energy deposition and machine learning. *Materials Science and Engineering: A* **891**, 145945 (2024).

68. Melia, M. A. *et al.* High-throughput additive manufacturing and characterization of refractory high entropy alloys. *Appl. Mater. Today* **19**, 100560 (2020).
69. Dobbstein, H. *et al.* Laser metal deposition of refractory high-entropy alloys for high-throughput synthesis and structure-property characterization. *International Journal of Extreme Manufacturing* **3**, 015201 (2020).
70. Tsai, P. & Flores, K. M. A combinatorial strategy for metallic glass design via laser deposition. *Intermetallics (Barking)*. **55**, 162–166 (2014).
71. Li, M., Gazquez, J., Borisevich, A., Mishra, R. & Flores, K. M. Evaluation of microstructure and mechanical property variations in Al x CoCrFeNi high entropy alloys produced by a high-throughput laser deposition method. *Intermetallics (Barking)*. **95**, 110–118 (2018).
72. Vecchio, K. S., Diplo, O. F., Kaufmann, K. R. & Liu, X. High-throughput rapid experimental alloy development (HT-READ). *Acta Mater.* **221**, 117352 (2021).
73. Vecchio, K. S. High-throughput (HTP) synthesis: Updated high-throughput rapid experimental alloy development (HT-READ). *Curr. Opin. Solid State Mater. Sci.* **31**, 101164 (2024).
74. Islam, Z. *et al.* A High-Throughput Method to Define Additive Manufacturing Process Parameters: Application to Haynes 282. *Metallurgical and Materials Transactions A* **53**, 250–263 (2021).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [20260507AutoSynthesisSupplementaryV33.2.pdf](#)
- [Video01WeighingClip01PlaceCupOnScale.mp4](#)
- [Video02WeighingClip02DispensePelletsIntoCup.mp4](#)
- [Video03WeighingClip03WeighingAndStacking.mp4](#)
- [Video04MeltingClip01CrucibleLoadingSequence.mp4](#)
- [Video05MeltingClip02MeltingSequence.mp4](#)
- [Video06MeltingClip03ButtonFlipping.mp4](#)