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LEVITATION MELTING OF METALS AND ALLOYS

by

J. W. Downey

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Metallurgy Division

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LEVITATION MELTING OF METALS AND ALLOYS

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ABSTRACT

Experimentation at Argonne National Laboratory has led to improved techniques for levitation melting, and our designs of two levitation coils have been qualitatively evaluated. The coils are capable of levitating small quantities of a wide variety of molten metals and alloys. A molten charge can be helium-quenched to a solid and yet remain levitated. Levitation melting is advantageous for the preparation of alloys that require the addition of a small quantity of a specific isotope, such as for studies of the Mössbauer effect. Alloys can be cast to predetermined shapes with such rapid cooling that segregation is minimized.

INTRODUCTION

Levitation melting is a recent technique for melting metallic materials by suspension of the dense charge in space with an electromagnetic field. An outstanding advantage of this method for the preparation of alloys is that a completely homogeneous melt can be produced quickly. Other attractive features of this technique include the following:

1. The molten charge can be solidified while levitated to minimize contamination by direct contact with other materials.
2. Alloys with a specific shape may be achieved in a direct manner by dropping the molten charge into a preshaped mold.
3. The ability to rapidly cool a specimen minimizes the amount of segregation upon solidification.

The technique has been used for a variety of purposes including alloy preparation,¹⁻⁴ vaporization studies,⁵ determination of the densities of liquid metals,⁶ and determination of thermodynamic properties of alloys.⁷ However, the preparation of small quantities of alloys for research purposes has received the most attention.

The feasibility of the technique for levitating molten metals was demonstrated by Okress *et al.*,⁸ and further refinements were indicated by Polonis *et al.*¹ Considerable attention has been focused on the design of suitable coils, the derivation of analytical expressions that relate the levitation forces to coil configuration, and the variable parameters associated with the generation of an electromagnetic field.^{4,9-11} Nevertheless, the fabrication of suitable coils and subsequent success in achieving the necessary levitation forces remain an art. The greatest hindrance to the utilization of this technique has been that the coil designs available in the literature are suitable for levitating only a limited variety of metals or alloys.

This investigation was initiated with the following objectives: (a) to develop levitation coils capable of melting a wide variety of metals and alloys, especially the transition-metal alloys; (b) to cast alloys into specific shapes directly from the molten state, particularly brittle intermetallic compounds that are not amenable to conventional shaping techniques; and (c) to develop a gas-quenching technique so that high-purity alloys in the liquid state could be quenched to the solid state without contamination by direct contact with other materials.

LEVITATION EQUIPMENT

The power generator was a commercial 10-kW, 450-Hz rf generator (described in Westinghouse bulletin 28-652). A bank of sixteen 0.03- μ F capacitors was connected in parallel with the output of the generator so that the capacitance could be varied to achieve the optimum frequency with a variety of coil designs.

The levitation furnace used in this work was obtained from the NRC Equipment Corporation.* The vacuum chamber consists of a 14- by 18-in. Pyrex cylinder mounted on a stainless steel plate. A removable aluminum plate serves as the top cover. Vacuum-tight seals are achieved by means of neoprene gaskets, situated at the interface between the ends of the cylinder and the cover plates that are compressed by means of tie rods. The chamber is connected to a vacuum manifold, which consists of a water-cooled baffle, a 4-in. diffusion pump, and a high-capacity mechanical pump. The complete equipment layout is shown in Fig. 1. The accessory components supplied with the furnace (specimen manipulator, specimen storage rack, mold table, and rotating dock) were removed and an 8 $\frac{5}{8}$ -in.-diam, 1/2-in.-thick copper plate was installed to serve as a sample mold table, which could be raised, lowered, or rotated with respect to the levitation coil (see Fig. 2). In the present work, quartz pedestals and copper molds were placed alternately on the periphery of the mold table, and the charge

*Newton Highlands, Massachusetts.

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Fig. 1. A View of the Levitation-melting Facility

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Fig. 2. A View of the Essential Components of the Levitation-melting Chamber Including the Coil, Gas Port, Mold Table, Molds, and Quartz Pedestals

to be melted was placed on the pedestals. The mold table was rotated so that the axis of the pedestal and the levitation coil coincided. At the appropriate time, the mold table was raised sufficiently to place the charge within the electromagnetic field of the coil. As soon as the power was turned on, the pedestal was quickly withdrawn and an adjacent mold, which was to receive the molten charge, was brought into proper alignment with the coil. After the charge was molten, it was cast into a mold by decreasing the power to the levitation coil.

Several coil configurations were tested during this investigation, and two were suitable for melting a wide variety of metals and alloys. The coils, designated A and B, are shown in Figs. 3 and 4. Although the two coils resemble previous designs,^{2,4} the overall dimensions (shown in Figs. 3 and 4) were increased to permit the melting of a larger charge, and copper tubing with an outside diameter of 3/16-in. rather than 1/8-in. was used to provide a greater cooling capacity. Coil A has $4\frac{1}{2}$ turns on the lower section, and two turns on the upper section wound in the opposite direction to those on the lower section. Coil B has $3\frac{1}{2}$ inner turns and two outer turns on the lower section, with $1\frac{1}{2}$ turns wound in the opposite direction on the upper section. The distance between the upper and lower sections of each coil was adjusted to provide optimum control and stability of the electromagnetic field. When moderately volatile materials were to

47356

Fig. 3. A Schematic Drawing Indicating the Configuration of Coil A. The indicated dimensions are in inches.

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Fig. 4. A Schematic Drawing Indicating the Configuration of Coil B. The indicated dimensions are in inches.

be melted, the coil was coated with an insulating material to prevent arcing between adjacent turns. Either Sauereisen Cement No. 78 or a porcelain enamel (No. SG-30339, supplied by Chicago Vitreous Corp.) provided sufficient insulation. The coils were operated at approximately 425 Hz; three capacitors were retained in the power circuit.

A gas port (the tube in the form of a gooseneck shown in the foreground of Fig. 2) was installed to permit the solidification of metals or alloys while in a levitated state. When a molten charge was to be gas-quenched, the port was rotated into a position coinciding with the axis of the coil. A relief valve, operative at 2 lb of positive pressure, was installed to release the additional pressure created during a gas-quenching operation. High-purity helium gas was used for all quenching experiments.

The design of a copper mold for casting a molten alloy is determined by the subsequent use of the alloy. Figure 5 shows two typical molds frequently used in this investigation. The major factor in the design of a mold is to provide contours and vents that will allow entrapped gases to escape; otherwise, voids will exist on the surface of the cast piece.

40104

Fig. 5. A View of a Tapered Mold and a Split Mold

OPERATIONAL PROCEDURE

The materials to be melted were placed on quartz pedestals, and the vacuum chamber was evacuated to a pressure $\sim 5 \times 10^{-6}$ mm Hg. The chamber was subsequently filled with argon gas. An inert-gas environment was usually preferred over a vacuum to reduce the evaporation rate of the molten charge and the possibility of arcing between successive turns of the coil. A charge of metal was placed in the coil, as described earlier, in a position between the upper and lower sections. To initiate levitation, the

generator power level should be set (before turning the generator on) for approximately 40% of the maximum rated power. Table I indicates typical voltage and current readings at the 40% power level for the two coils. After the sample was levitated, the power level was altered to achieve the optimum conditions for the material being melted. While the sample was suspended, the pedestal was withdrawn and the appropriate mold was located approximately 1/2 in. below the coil. After several seconds had elapsed to ensure homogeneity and sufficient superheating of the charge, the power was reduced to allow the melt to pour into a copper mold.

TABLE I. Typical Rf Generator Voltage and Current Values to Initiate Levitation Melting

	Plate Current, Amp	DC Plate Voltage, volts	Rf Voltage, volts	Rf Current, Amp
Coil A	1.5	7000	850	160
Coil B	1.62	6800	800	150

When a helium-gas quench was desired (the helium gas was pre-cooled with liquid nitrogen to provide a faster quenching rate), the gas port was rotated into a position directly under the coil and a steady flow of gas was released without reducing the generator power. When the alloy had solidified, the power was reduced and the charge fell on the mold table. Figure 6 shows a 3-g charge of pure aluminum that was quenched to the solid state with helium gas while levitated in space. Pure metals with higher melting points, such as zirconium, titanium, and vanadium have also been quenched to the solid state by this technique.

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Fig. 6. A 3-g Charge of Aluminum Solidified by Helium Quenching

EXPERIMENTAL RESULTS

The successful levitation of metallic materials with any coil configuration requires that the initial charge have a physical shape approaching a sphere or a cube to ensure stability in the electromagnetic field. Otherwise, the solid charge

may contact the insulating material on the coil and become contaminated or, in the case of an uninsulated coil, may short out successive turns and terminate the melting operation. The charge may be in the form of several solid pieces, powdered compacts, or a combination thereof, provided the geometrical requirement is met. Also, the present experiments indicate that a hemispherical button, produced by nonconsumable arc-melting techniques, can be melted directly in the levitation furnace.

The vapor pressure of the component metals is another important factor that determines the applicability of this technique to the preparation of alloys. Elements with a moderately low vapor pressure in the liquid state generally do not present any difficulty. If a volatile component is a part of the charge, levitation melting can be achieved provided (a) the metallic vapor does not produce arcing between successive turns of the coil, and (b) the net weight loss does not appreciably change the final alloy composition.

Table II presents a qualitative assessment of the two coil designs for levitating and melting elemental metals. The mass of the materials indicated in the table is not necessarily the maximum quantity that can be successfully levitated or melted with these two coils. The tabulation indicates that Coil B has a better levitation melting capability for a greater number of elements than Coil A. However, Coil A has a larger inside diameter and is therefore capable of handling larger charges. The two coils cannot melt six of the transition elements with high melting points--niobium, molybdenum, tantalum, tungsten, rhenium, and osmium. When the six transition elements are alloyed with elements that have lower melting points, successful melts can be obtained, as indicated in Table III. Rhenium is the only transition element that could not be successfully levitated with the two coil configurations.

Various solid-solution alloys and intermetallic compounds have been prepared successfully by levitation melting, and representative examples are listed in Table III. Levitation melting can often yield homogeneous alloys that are not easily obtained by nonconsumable arc-melting techniques. For example, a 10-g charge of titanium and molybdenum with an atomic ratio of 7:3 was arc-melted three times. Subsequent metallographic examination revealed an incomplete solution of molybdenum. An equivalent alloy was melted in the levitation furnace, held in the liquid state for $1\frac{1}{2}$ min, and quenched in a copper mold. A thorough metallographic examination revealed complete solution and mixing of the constituents. Also, a chemical analysis fixed the composition of the alloy at 69.7 a/o titanium and 30.3 a/o molybdenum.

TABLE II. Relative Assessment of Ability of Coil Arrangements to Levitate and Melt Certain Elements

Element	Coil A			Coil B		
	Mass, ^a g	Levitation Ability ^b	Melting Ability ^c	Mass, ^a g	Levitation Ability ^b	Melting Ability ^c
Sc	5	1	a	3	1	a
Ti	2-10	1	a	2	1	a
V	4	1	a	3	1	a
Cr	3	1	a	3	1	a
Mn	2	1	a	1	1	a
Fe	5	1	a	5	1	a
Co	4-8	1	a	1	1	a
Ni	2	1	a	2	1	a
Cu	3	1	a	1	1	a
Zr	2-11	1	a	1	1	a
Nb	5	3	b	1	3	b
Mo	2-30	3	b	2	3	b
Ru	2	2	a	3	1	a
Rh	2	2	a	1	1	a
Pd	2	4	b	3	1	a
Ag	3	1	a	1	1	a
Hf	2	2	a	2	1	a
Ta	2	4	b	2	3	b
W	2	4	b	1	3	b
Re	2	4	b	2	4	b
Os	2	4	b	3	3	b
Ir	3	2	a	3	1	a
Pt	2	4	b	1	1	a
Au	1-4	2	a	2	1	a
Al	1-10	1	a	1	1	a
Si	1	4	b	1	4	b
Sb	2	2	a	2	1	a
Sn	3	1	a	3	1	a
Th	2	4	b	3	1	a
Ge	2	1	a	1	1	a
Ca	-	-	-	1	1	a
Tb	-	-	-	1	1	a

^aThe mass reported is the quantity used in the present investigation and is not necessarily the maximum quantity that can be successfully levitated in the two coils.

^b1--easily levitated in both the solid and the liquid states.

2--can levitate in the solid state, but the charge drops out of the coil upon melting.

3--easily levitated in the solid state.

4--cannot levitate in the solid or the liquid state.

^ca--easily melted.

b--cannot melt.

TABLE III. Alloys Successfully Prepared by Levitation Melting

Coil A		Coil B	
Alloy	Mass, g	Alloy	Mass, g
ZrMo ₂	5	Pd-2 a/o Fe ⁵⁷	1
WFe ₂	5	Pd-4 a/o Fe ⁵⁷	2
ReFe	3	V-2 a/o Fe ⁵⁷	2
TiMn	5	Pd-Cu ^a	5-10
V ₄ Fe	3	Pt-Fe ^a	3
V ₄ Fe ⁵⁷	1	Ru-Rh ^a	1
Nb ₃ Sn	3	Rh-Pd ^a	5
Ti ₂ Ni	2	Fe-Ge ^a	7
UFe ₂	3	Fe-Sn ^a	10
U-Ti ^a	3	Fe-Sb ^a	7
Ag-Au ^a	4	Al-Ge ^a	3
V-Mn-Cr ^a	5		
U-Fe-Al ^a	5		
Zr-Be ^a	5		
Zr-Si ^a	5		
VMn ₃	3		
V ₂ Mn ₃	4		
Ti ₇ Mo ₃	10		
Cu-Ag ^a	7		

^aAlloys were successfully levitated over a wide range of composition.

The levitation-melting technique is an ideal method for the preparation of alloys for Mössbauer studies that require a small quantity of a suitable isotope. For example, small quantities of Fe⁵⁷ were successfully added to vanadium and palladium, as indicated in Table III, to produce a homogeneous distribution of the isotope. The procedure used is as follows: The alloy component was levitation-melted and cast into a mold. A small hole was drilled into the center of the cast material with sufficient volume to contain small quantities of the isotope. To prevent mechanical losses in the process of remelting, the hole was closed by deforming the material immediately adjacent to it.

Another useful application of the technique is the ability to cast samples into a specific shape directly from the liquid state. For example, saturation magnetization measurements require samples in the form of an ellipsoid or a sphere in order to calculate the corrections for the demagnetization field. Although this capability is useful for all materials, it is particularly advantageous for brittle alloys and compounds that cannot be deformed by conventional fabricating techniques. An alloy can be cast directly

in the form of a sphere or a right circular cylinder; the latter can be easily ground to an ellipsoid. Also, pin-shaped specimens of brittle compounds are readily cast for other property measurements. Our experience suggests two major factors that dictate the successful casting of a specific shape in a copper mold:

1. The solid-liquid interface must move progressively from the bottom of the mold (or closed end) to the top (or open end) to ensure the absence of shrinkage cavities.
2. If the shape of the mold is such as to allow gas pockets to remain in situ, a vent must be provided for the gas to escape so as to eliminate surface cavities.

A molten charge within a levitation coil need not be cast in a mold of predetermined shape. Frequently, it is desirable to convert elements of high purity from a powder or sponge form to a solid form while maintaining the purity. This may be accomplished by compressing the material into compacts that are then levitation-melted. A helium-gas quench is used to prevent direct contact of the molten charge with other materials. Also, metals and alloys may be obtained in the form of a thin disc. A disc is produced when a molten charge is dropped directly on the copper mold table; this provides an extremely rapid quenching rate because of the large surface area in contact with the table. Figure 7 shows some of the shapes produced during this work.

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Fig. 7. A Variety of Levitation-melted Samples. Top Row--Samples cast into the molds shown in Fig. 5. Materials shown from left to right, Zr, Pd, V, TiMn, and Zr. Center Row--Helium-quenched samples. Materials shown from left to right, eight Zr, V, ZrMo₂, and Fe. Bottom Row--Samples that were dropped on the copper chill plate to produce discs. Materials shown from left to right, Zr, Th, Ni, Hf, and Ti.

SUMMARY

The principal limitation to the use of the levitation-melting technique has been the lack of a coil design that could be employed with a variety of metals and alloys. To overcome this barrier, two coil configurations have been developed that permit a wide variety of metals and alloys to be levitated successfully in the molten state. Although only limited quantities of material may be processed with the present coils, the quantities are typical for research purposes.

Various techniques were developed that are unique to this method of alloy preparation. A helium-gas-quenching method has been described that minimizes contamination and segregation. Since the molten charge can be suspended in space, it was convenient to cast alloys into molds with a variety of predetermined shapes. The preparation of alloys for Mössbauer studies, which contain a small quantity of a suitable isotope, were successfully prepared by the levitation-melting technique.

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