The joining of wires to various substrates (wires, plates, foils and semiconductor packages) is a ubiquitous process in the manufacture and modification of electrical and electronic devices. While spot welding is used extensively to attach lamp and vacuum tube filaments to base wires and foils, soldering is almost universally used to make chip to package and wire to substrate interconnections in electronic devices (Refs. 1-3). Reliability problems with joints made by using these techniques stem from failures associated with mechanically and thermally induced stresses, surface contamination, the complex metallurgy of multiple layers and thermal expansion mismatch between the chip or substrate and the solder.

This article reports the results of a feasibility study of a new joining technique that may overcome many of these problems. The new technique, called DROW (droplet welding), for joining (welding) metals on a scale appropriate for electronic and electrical connections is made possible by the recent development of the novel generator of monodisperse metal droplets (GEMMED) (Refs. 4-7). The GEMMED is a pulsed microarc device that produces spherical, 50-1000-µm-diameter, high-temperature metal droplets and uniquely provides uniform metal droplets with controlled, repeatable droplet size, temperature and trajectory. Droplet initial velocity varies in the 0.5-5 m/s range depending on the metal and the droplet diameter.

Joining in DROW is achieved by deliberate deposition of high-temperature metal droplets (filler metal) on the site of contact of the joined components. Therefore, only the filler metal is heated by the microarc. When the droplet impinges on the surfaces, its heat content produces localized heating and melting of the components to be joined. The ability to control the size and initial droplet temperature allows one to tailor the extent of heating (melting) to the requirements of the joint.

Because DROW applications can use essentially any metal as the weld filler, it is expected that DROW will allow filler material to be selected to reduce or eliminate mismatch problems and to simplify the metallurgy of the joints. The absence of fluxes in DROW should reduce surface contamination problems, and the mechanical strength of the welds should be higher than those of brazed or soldered connections. In contact welding (spot welding) applications, reliability is the major problem, especially when refractory metals are welded together as in lamp and vacuum tube applications. DROW is a completely new approach to the welding of small specimens of refractory materials; it makes a conventional weld joint instead of an electrically fused joint. Reliability and strength should also improve.

**APPARATUS**

The heart of the experimental apparatus, schematically presented in Fig. 1, is the GEMMED. The GEMMED produced metal droplets and directed them at the contact point between the materials to be joined. The temperature of the freely moving droplets was monitored by an optical pyrometer. The pyrometer output signal, as well as the microarc current, was recorded by a digital oscilloscope for later analysis.

**GEMMED**

Droplets are formed in the GEMMED by the rapid melting of a free edge of a consumable (metal) wire anode in a pulsed microarc discharge (Refs. 6, 7). During each microarc pulse a small area of the anode wire is initially fused to begin forming
a droplet. Anode material melts until the droplet is at maximum size, which is
determined by the criterion of the balance of the droplet surface tension with the
electron pressure and electrodynamic forces (Ref. 8). At the end of the microarc pulse,
the molten droplet breaks away from the anode, leaving at a reproducible velocity, size
and temperature each time the anode wire is advanced and the microarc pulse is
repeated. The droplet cools in the surrounding gas as it travels to the weld area. The
extent of cooling is determined by the droplet size, time of travel and gas
temperature/composition (as this implies, the gaseous environment may be controlled).

The GEMMED built for this research includes a manual wire feed unit, a microarc
pulse generator and an electrode unit — Fig. 1. The wire feed unit is similar to
commercially available wire feed systems used in automated welding machines and
differs in scale rather than concept. It consists of a spool holder, two wire guides and
manual drive cylinders. The two wire guides were used for electrical contact with the
wire as well as to guide the wire into the microarc formation zone.

The microarc generator produces two pulses: a 1-2-µs high-voltage gas discharge
ignition pulse and a controllable duration (10 µs to 50 ms) high-current pulse for the
main microarc. The pulse train is initiated by a 10-V pulse formed by a Datapulse-110B
pulse generator. The ignition pulse is produced by using an active differentiating circuit,
its output being connected to a pulsed high-voltage transformer. The microarc pulse is
formed by sequentially amplifying in voltage and current the precision pulse produced
by the pulse generator. The voltage output in the range of 40-55 V is determined by
a regulated stabilized power supply (Kepco SM 36-5AM) to the voltage amplifier. The
current amplifier is powered by a custom regulated 50-75-V power supply and
produces a pulse of equal duration and voltage but having a current as high as 120
A, as determined by the load.

The electrode unit consists of a copper tool cathode and a consumable wire anode.
The configuration of the electrodes is schematically illustrated in Fig. 1. The cathode
is mounted on a three-dimensional positioning stage. The interelectrode position is
adjusted manually by using a direct measuring microscope. Experiments were
conducted in air and in flows of nitrogen or argon formed by using two copper tubes
of 0.5 mm internal diameter, attached to the cathode and directed at the weld region.
The gas flow velocity did not exceed 0.5 m/s and had a negligible effect on the
diameter and temperature of the formed droplets.

OPTICAL PYROMETER

The filler metal droplet temperatures were monitored with a two-wavelength
pyrometer, similar to those successfully used in temperature measurements of moving
metal droplets in spray coating research (Refs. 9, 10). The size and temperature range
of metal droplets used in spray coating [40-100 µm, 2000-4000 K, (Ref. 10)] are similar
to the droplet parameters in the present work. If the metal emission spectrum
corresponds to gray body radiation, then the temperature computed from the ratio of
emission intensities measured for close wavelengths will correspond to the actual
temperature. This is, in most cases, correct for metal radiation. An assumption
accepted for the use of a two-wavelength pyrometer is that emissivity values are close
for the wavelengths used. This assumption is justified by choosing close wavelengths
for the emission intensity measurements. The pyrometer used in this work included an
iris, a fiber-optic bifurcated bundle, two interference filters and two HC120-01
Hamamatsu photosensor modules. The 540- and 580-nm interference filters were
available for this work and had a central wavelength determined with an accuracy of
±2 nm, a peak transmittance higher than 50% and a half-bandwidth of 10 nm. Each
of the photosensor modules includes a 1/2-in., side-on photomultiplier tube with a
spectral range of 185-650 nm. A multichannel digital oscilloscope (Rapid System R1000) was used for the data acquisition. The pyrometer was calibrated using a tungsten strip lamp providing a maximum black body temperature of 2400 K. The calibration curve was extrapolated to 5000 K using a Planck-type expression with constants chosen to fit the measured curve.

**SAMPLE POSITIONING**

Test substrates were supported on a three-way translation stage to position them relative to the droplet trajectory. The wires to be joined were secured by spring action, crimping or a precision single fiber holder developed to adjust and fix the position of optical fibers.

**EXPERIMENTAL SECTION**

The experimental procedure for producing and testing droplet welds generally consisted of the following steps:

**STEP 1: FILLER METAL CHOICE**

Depending on the compositions of the materials to be joined, one or more metals to be used as filler metal were chosen. The main consideration in making that choice was that the droplet of filler metal be reliably produced at a temperature higher than the melting point of the components to be joined.

**STEP 2: FILLER METAL DROPLET PRODUCTION**

An appropriate wire size for the consumable anode is a diameter close to the radius of the droplets to be formed. GEMMED operational parameters were found that provided repeatable formation of the chosen size and temperature filler metal droplets. Droplet diameters and temperatures were adjusted by varying the electrode position and microarc current (Refs. 6-8).

Droplets were quenched and cooled in room temperature water. Their size was then measured with an optical microscope. It is recognized that the solid particle diameter differs somewhat from the droplet diameter. The average error of size measurements is estimated to be ±10% in this work.

The temperature of copper and molybdenum filler metal droplets during their trajectory was monitored by using the two-wavelength optical pyrometer. Ambient gas was controlled by using a gas flow directed to the electrode unit. Room air (no gas flow), argon and nitrogen were used in this program.

**STEP 3: SURFACE INTERACTION TESTS**

The materials to be welded were positioned as flat surfaces or large diameter wires on the sample holder. Droplet parameters and distance from the electrode unit to the sample were varied to find conditions that reliably gave droplet welding into the substrate (without using the second component to be welded). As a rule, the substrate surface was cleaned before the experiments. Aluminum and iron-based alloy substrates (iron, Kanthal and Kovar) were mechanically degreased with an abrasive or an emery cloth. The copper surface was degreased by applying ammonium hydroxide and a single-step surface cleaning solution containing potassium hydroxide. A solution of \( \text{K}_3\text{Fe(CN)}_6 \) (Refs. 13, 14) was used for cleaning the tungsten and molybdenum surfaces.

**STEP 4: WELD PRODUCTION**

Two classes of welded joints were attempted in this work: joining of two comparable diameter (thin) wires and joining a thin wire to a bulky substrate, namely, a large diameter wire or a plate. Both components to be joined were mounted on the sample holder beneath the GEMMED electrodes. The position of the components was adjusted
to the droplet trajectory with the translation stage. Welds were produced by using the nominal conditions found in step 3, with the droplet initial temperature and distance from the weld site to the electrode adjusted as necessary. A series of welds was produced in each ambient gas for most welded component combinations.

**STEP 5: WELD DIAGNOSTICS**

Welds were visually inspected through an optical microscope. This showed the general shape of the bead and the welded wire as well as metal surface texture. Selected welds were analyzed by using a pull strength test or were cross sectioned for microstructural analysis.

Weld samples for microstructural examination were embedded in epoxy. The microsections for metallographic microscope analysis were prepared by using abrasives recommended in Refs. 16 and 17.

Microhardness tests were conducted by using a Model M-400-H1 LECO microhardness tester equipped with a VL-101 Video-Line Type TV measuring system. Electron microscope weld cross section examinations were carried out with an AMRAY 1800 scanning electron microscope (SEM) with a PGT prism energy dispersing spectroscopy detector.

Pull strength tests were conducted using a Tinius-Olsen universal testing machine. A load cell with a maximum force of 50 N was used. Special attachments for holding fine wire weld specimens in the testing machine grips were constructed. Welded wires or wire and substrate were mounted in the grips of the testing machine, and the force needed to destroy the weld sample was determined. If the wire broke within 10 diameters of the weld, the result was considered a weld failure. Reference pull strength tests of wires similar to the welded ones were conducted before each weld strength test. The relative weld strength was calculated as \( \frac{F_{\text{weld}}}{F_{\text{wire}}} \times 100\% \), where \( F_{\text{wire}} \) was the force required to break the wire and \( F_{\text{weld}} \) was the force needed to break the weld.

**RESULTS AND DISCUSSION**

This feasibility research was organized as a survey of DROW capabilities, rather than as a systematic study of the effects of different variables on the weld parameters. The summary of the data describing the welds produced in this work is presented in Table 1. These data show that many materials were successfully welded and many welded joints have been produced, for which the weld strength was equal to or greater than the strength of the joined components (when the wire was broken and weld withstood the test, it marked as having a weld strength of 100% in Table 1).

**FILLER METAL DROPLET INTERACTION WITH A FLAT SUBstrate**

The first important condition for weld production with this process is that a filler metal droplet stick to the welded components or, in a simple model case, to a substrate, rather than bounce on collision. Some previous work carried out to determine the factors affecting droplet rebound or sticking to various surfaces (Refs. 12, 17) was used as a starting point for experimental design in this research. In that work the rebound-sticking phenomenon was found to be related to the ratio of the droplet-surface contact time to the time for the particle to cool (by heat transfer to the surface) to its freezing point. For the (small) range of GEMMED-produced droplet velocities, the contact time was taken to be the period of a free oscillation of the metal droplet (see, e.g., Ref. 18); the heat transfer rate for droplet cooling was numerically obtained from the thermal conductivities and heats of fusion of the droplet and substrate and an estimate of the contact area. It was found (Ref. 17) that large values of this ratio (i.e., those with large rates of cooling and hence small times to cool to the freezing point) result in sticking while smaller values (slow cooling) result in rebound.
Even though this criterion predicted sticking for all of the droplet-surface collisions of this work, there were many nonsticking events observed. In addition, not all sticking collisions led to weld formation. The observations and insights gained are discussed here.

Bouncing was often observed if the substrate surface was not precleaned. Therefore, it can be assumed that an oxide layer and/or a thin grease layer existed on metal surfaces and affected the interaction. However, bouncing was also observed in some experiments with cleaned copper, molybdenum and tungsten surfaces, suggesting that a more detailed analysis of the interaction is required. Temperatures were monitored during the bouncing of molybdenum and copper droplets from clean molybdenum and copper surfaces, respectively. Molybdenum droplets were observed to bounce in two different temperature ranges: above 4800 K and below 3300 K. Copper droplet bouncing occurred in the temperature range 1900-2700 K. Interestingly, droplet temperatures were not observed to decrease considerably during the collisions. However, changes in the texture and microstructure of the substrates, observed in many cases at the collision locations, showed that some local melting of the substrate layer occurred. This suggests that there was no significant surface layer (e.g., grease or oxide) preventing heat transfer from the droplet. A unique feature observed in the bouncing of copper droplets from copper surfaces was that a thin residue layer of the bounced copper drop remained on the substrate. It contained approximately 10% of the original (bounced) droplet metal. A micrograph of a cross section of such residue layer is shown in Fig. 2. The microstructure of the copper foil under this residue layer shows that the foil was partially melted. This infers a bouncing mechanism involving droplet parameter gradients (e.g., surface tension gradient) arising in the droplet upon the collision rather than integral droplet cooling or oscillations.

As noted above, droplets that stuck to flat substrate were not always associated with welded bond formation. In the majority of the “sticking without welding” cases the substrate surface was not precleaned. However, there were several tests using mechanically and chemically cleaned molybdenum, tungsten and copper substrates in which sticking without weld formation was also observed. Sticking without weld formation was observed for the following droplet-substrate interactions: copper droplets (above 450 µm) with copper substrate; tungsten and tantalum droplets (170-450 µm) with molybdenum substrate; molybdenum droplets (170-450 µm) with molybdenum and tungsten substrates. For some cases of sticking of tungsten droplets to molybdenum substrates, it could be seen that the substrate was melted. However, there was no welded bond formed and the solidified tungsten particles could be easily removed.

The experimental conditions that led to sticking with weld formation were monitored for copper and molybdenum droplets welded to copper and molybdenum substrates, respectively. Substrate surfaces were cleaned before weld production. Molybdenum to molybdenum welds were successful when the droplet temperatures were in the range 3800-4300 K. Successful copper-copper welds were produced with droplet temperatures in the range 1800-2750 K. It should be noted that these rather broad temperature ranges do not ultimately provide a successful weld but do indicate within what limits the droplet temperatures should be kept, while varying their diameters and velocities to achieve acceptable joints.

The data relevant to metal droplet sticking/bouncing collected in this research have indicated that substrate surface treatment can be crucial for the droplet-substrate interaction result, and even a thin oxide or grease layer may result in droplet bouncing or prevent weld formation. It also seems apparent that the analysis based on the comparison of the time of droplet cooling via heat conductivity to bulk substrate and the time of contact (Refs. 12, 17) is oversimplified for many cases of interactions of
a hot metal droplet and a room temperature metal surface. A more detailed study of the collision is needed to understand the mechanisms affecting the collision and weld formation. Such a study should address the processes resulting from the temperature, surface tension and viscosity gradients in the droplet and the molten part of the substrate. Clearly, droplet temperature, size and velocity can substantially affect the collision results; however, it is currently not possible to point out a range for either one of these parameters for which sticking or bouncing can be definitely predicted. From the practical standpoint, the successful welds produced in this work show that the GEMMED is able to produce droplets with the diameter, temperature and velocity required for the droplet welding method.

FORMATION OF WELDED JOINTS BETWEEN WIRES AND FLAT SUBSTRATES

When weld metallic bonds were formed, the interactions of high-temperature metal droplets with wires positioned on substrates resulted in one of the following:

1) The droplet was “frozen” on the wire without contacting the substrate
2) The wire was melted through by the droplet, which melted into the substrate
3) A welded junction of the wire on the substrate was formed

Which of these resulted from the interaction was found to depend on the droplet/wire/substrate materials, droplet/wire size ratio and droplet temperature. For each of the droplet/wire/substrate combinations examined in this work (see Table 1) all three results were observed. In general, it was found that a weld can be produced when the filler metal droplet size is considerably (4-5 times) larger than the diameter of a smaller joined wire. In successful welds, a bead formed out of the filler metal drop enclosed the smaller wire and was attached to the substrate (in the case of two comparable diameter wires, both of them were included in the formed bead). When too small a drop was used, it only welded to one of the components. The reason for this is that small drops cool rapidly upon contact with the first component they strike, so the heating of the second component was insufficient to produce a welded bond. Larger drops tended to burn out the wires.

The gaseous environment was observed to affect the appearance (and, as will be discussed further, mechanical properties) of the welds. Smoke clouds observed around metal droplets in air faded in inert gases. Metal beads formed in inert gas had a shiny “metallic” surface without pores. Similar welds produced in air by using refractory filler metal droplets (molybdenum, tantalum and tungsten) had a black surface with many small pores, which can be explained by surface oxidation of metals in air.

Interestingly, the separation of the wire from the substrate, established prior to welding, did not noticeably affect the weld formation as long as the separation was less than the droplet radius. A microscopic cross section of a tungsten wire to a Kanthal substrate weld produced by using a molybdenum droplet, presented in Fig. 3, shows that the welded joint is formed in spite of the wire being initially positioned at a considerable distance from the substrate. The ability to produce such welds is important from both fundamental and practical standpoints. Fundamentally, it shows that it is possible to choose droplet parameters so that it will not burn out a fine wire at the interaction but will heat and melt both the wire and substrate to form a welded joint. Practically, it shows that for DROW joint formation it is not required to bring joining components in physical contact (as is required for spot welding), a possible advantage in welding fine and brittle components used in the electronics and lamp industries.

WELD MICROSTRUCTURE

Cross sections of the welds produced by using refractory filler metal droplets showed no internal voids or fracturing while multiple rounded holes have been
observed inside the welds produced by using aluminum and copper filler metal droplets — Fig. 4. Similar holes were observed in copper welds produced in air, nitrogen or argon flow. The larger number of holes and the increase of their size were noticed when higher temperature copper droplets were used. The smooth shape of the observed voids suggests that they originated in a liquid droplet well above the melting point. The mechanism of void formation may be associated with gas entrapment in high-temperature metal (Ref. 19).

Microscopic examination of the material interfaces in the weld structures revealed interesting effects. All the observed interface structures can be divided into three general groups:

1) The interface can be seen as a boundary between two different materials, and its shape and position appear to be the same as those of the original interface in the droplet/wire/substrate system (example: the copper-iron weld shown in Fig. 4).

2) The interface cannot be seen, or the structure of the welded components is merged with the filler metal droplet structure (examples: copper-copper and molybdenum-tungsten welds; see, e.g., Fig. 3).

3) The interface can be clearly seen, however, it reveals a strong interpenetration and mixing of the filler metal and welded components; its shape is strongly distorted compared to the shape of the original interface in the droplet/wire/substrate system (examples: tungsten-Kanthal and molybdenum-Kanthal welds, see Figs. 3 and 5).

For the first type of interface, the energy dispersing spectroscopy (EDS) analysis has shown that the substrate-droplet metals are mixed in a zone with a thickness of ca. 15 µm. This is a typical size zone expected for a diffusive mixing mechanism.

The second type of interface shows the formation of an alloy when two different metals are involved (e.g., molybdenum and tungsten) or simply uniform mixing of the same molten metal from the droplet and substrate.

The third type of interface was analyzed by using EDS in a molybdenum wire to Kanthal substrate weld. It was found that iron, chromium and aluminum (Kanthal components) intrude deep into the solidified molybdenum filler metal drop, penetrate into droplet/wire gaps and produce Kanthal-molybdenum alloy layers with approximately 35-40 wt-% molybdenum. Formation of a thin film of the substrate material on the weld surface and penetration of the substrate material inside the refractory metal bead is demonstrated in Fig. 6. Figure 6A is an overall view of the cross section of the Kanthal and molybdenum wires welded with molybdenum filler, and Fig. 6B shows an iron concentration map of the weld produced with EDS. It can be seen that an iron-containing thin film covers all the weld surface. These transport phenomena may result from Marangoni stresses (Ref. 20) at the molten metals if the initial droplet temperature is considerably greater than the substrate melting point and it causes a local melting of the substrate material.

WELD MECHANICAL PROPERTIES

The results of the weld pull strength measurements are summarized in Table 1. The data shown in Table 1 represent the best results (or the strongest welds produced with corresponding materials) obtained in this work. We consider such a presentation appropriate for the demonstration of weld formation feasibility. It should be noted that, in all the pull strength tests, excluding the tests of copper on silicon welds, the welded wires were destroyed in the vicinity of the weld while the welds themselves withstood the tests. Microscopic examination of the weld cross sections showed that the cause of such weld failures could be explained by the change of the wire structure (increase of crystal grain size) in the vicinity of the weld, resulting in wire brittleness.
Copper-silicon welds were destroyed by breaking the brittle silicon substrate. Fragments of silicon attached to the weld were broken along intercrystal grain boundaries in the pull strength tests.

Microhardness measurements were carried out for a tungsten to Kanthal weld made by using a molybdenum droplet. They also clearly showed the effect of thermal treatment on the wire hardness in the vicinity of the weld. The microhardness increases from typical for the wire 520 to a maximum of 880 Knoop units as the distance from the weld decreases from 12 to 5 wire diameters.

Structure change is typical for any welded joint and is strongly affected by the metal composition and, especially, by the dissolved gases. The effect of oxidation on the mechanical strength of refractory metal welds was tested by comparing similar tungsten to Kanthal welds produced by using molybdenum droplets in atmospheres of air and nitrogen. The welds made in nitrogen were strong (100% of the wire strength, as shown in Table 1) while the welds made in air were very brittle and were destroyed by a force close to 10% of the wire strength value. On the contrary, no significant effects of ambient gas on weld strength were noticed, for the welds that used copper and aluminum filler metal droplets.

CONCLUSIONS

Experimental results obtained in this research have demonstrated the feasibility of a novel DROW method for producing wire to wire and wire to surface miniature joints for a wide range of components and materials used in the electrical and electronic industries. The diameters, temperatures and velocities of GEMMED-produced droplets were found to correlate well with the parameters required for welding. The capability of DROW to produce strong welded joints between the components that are brought in physical contact before welding as well as between the components that are simply positioned close to each other, even without physical contact, has been demonstrated. Substrate surface preparation was found to be crucial for many cases; however, environmentally friendly and readily available chemical compounds were used for the surface cleaning.

It has been shown that filler metal droplet diameters should be 4-5 times larger than the diameters of the wire joined to substrates. The metal beads formed out of the filler metal droplets enclose the wires in acceptable welds.

It was observed that droplet temperature and size can significantly affect the weld formation process. It is anticipated that droplet velocities will be found to impact the welding. The need for a detailed study of droplet diameter, temperature and velocity effects on DROW process has been identified.

Added material

EDWARD L. DREIZIN is with AeroChem Research Laboratories, Inc., Princeton, N.J.

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Table 1 — Summary of the Data Characterizing the Welds Produced by DROW

<table>
<thead>
<tr>
<th>Wire 1 Thickness</th>
<th>Wire 2 Diameter</th>
<th>Droplet Diameter</th>
<th>Weld Strength, (% of wire)</th>
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Material (µm)       Material (µm)       Material (µm)       strength
Kanthal  700         Cu  51         Cu  170
W       25           Mo  170       Ta  170
          102         Mo  420
Mo       25           W  170
Ta       170

Cu  254         Cu  254         Cu  730
51        Nichrome 51        Cu  170
74        Monel        51        Cu  170
Copel  203         Chromel-A 160       Cu  720

Wire to Substrate
Substrate             Wire                      Droplet           Weld
Strength,              Diameter               Diameter    (%   of wire
Material     (µm)      Material       (µm)     Material    (µm)      strength)
Fe            500        Al              51        Cu          170
Cu            51        Cu            51        Cu          170
          102         Cu            460       100.0(FNa,b)
          254         Cu            730       100.0(FNa,b)
Mo            254         Mo            410       69.1(FNa,b)
Al            1000        Cu              51        Cu          170
Cu            40        Cu            40        Cu          170
          67        Cu            67        Cu          170
          127        Cu            730
          203        Cu            730
Tinned Cu      67        Cu            67        Cu          170
          127        Cu            730       100.0(FNa-c)
          203        Cu            730       62.2(FNb)
          102        Al            460       100.0(FNb)
Si            300        Cu              51        Cu          170
                51        Cu          170       13.2(FNb)
Mo            100        Mo              25        Mo          420
W             70         W             25        W          180

FOOTNOTES
   a Produced in nitrogen.
   b Produced in air.
   c Produced in argon.

Fig. 1 — General scheme of the experimental setup.
Fig. 2 — Cross section of the residue of a copper droplet left on the copper foil after droplet bouncing. Magnification 100X.
Fig. 3 — A — Cross section of a molybdenum wire welded to a Kanthal wire by using a molybdenum droplet. Magnification 300X; B — Fragment of the cross section of a molybdenum-Kanthal weld showing the substrate material (Kanthal) forming a shell around the bead. Magnification 400X.
Fig. 4 — Cross section of a copper droplet welded to an iron foil.
Fig. 5 — Cross section of a molybdenum wire welded to a Kanthal wire by using a molybdenum droplet. Magnification 200X.

Fig. 6 — A — Overall view of the cross section of a molybdenum wire welded to a Kanthal wire by using a molybdenum drop. The SEM produced — B — molybdenum map and — C — the SEM produced iron map of this weld.

REFERENCES