Soldering Silver to Aluminum and Copper for Cryogenic Applications

Cryogenic evaporators were manufactured by soldering with silver heat-conductive plate to explore the internal design range of a possible electronics cooling solution

BY LEONID A. SHAPIRO

Microprocessor design has recently turned in another direction relative to the past 30 years. The emphasis is now placed on spreading computational workloads to multiple smaller, separated devices. This change was brought about in part as a solution in electronics cooling (Ref. 1). Consistent miniaturization of transistor parts decreases thermal resistance and power consumption per part, but growing device complexity and part density increase the heat flux at the device's surface, necessitating more formidable and massive cooling items to prevent heat-induced materials-expansion-related stresses and current leakage (Refs. 2, 3).

Moreover, the future is invariably that of mobile devices.The market is driven by demand from consumers for mobility, and power inefficiency is now a primary concern. Although microprocessor manufacturers presently increase the overall number of processors, while lowering operating clock frequency per processor, and produce dies wherein multiple otherwise self-contained processor cores exist on a single processor die, that methodology is but a successful temporary compromise between increased device performance and its heat output, since increases in the number of processor cores can only provide marginal benefits. It's the law of decreasing marginal utility. Efficient distribution of software tasks is not possible in many circumstances, and miniaturization of transistor parts cannot continue forever (Ref. 4).

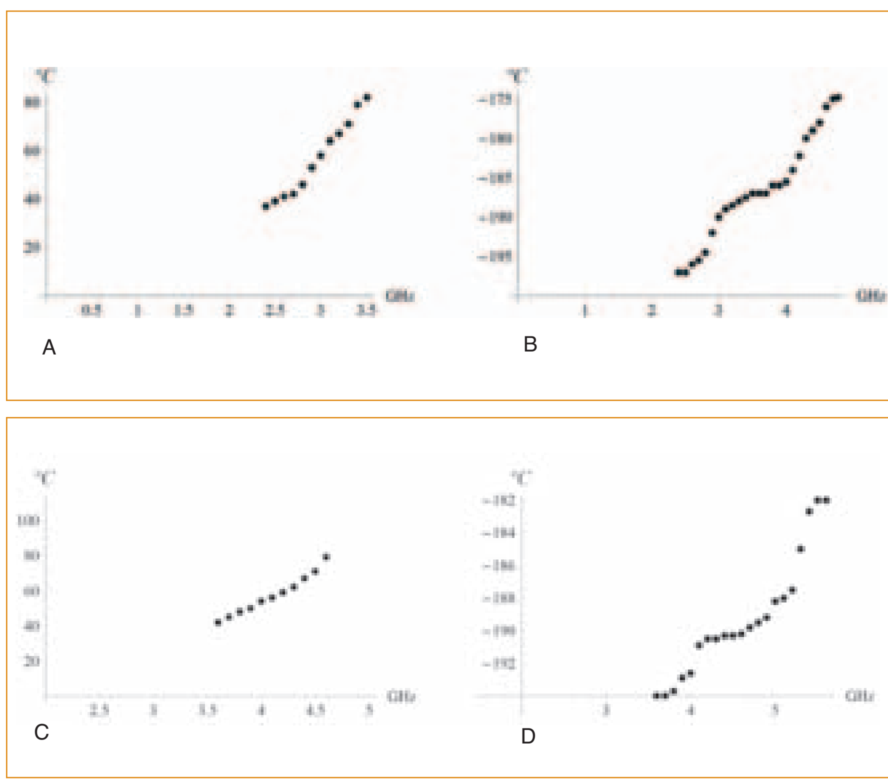

Fig. 1 — Mean temperature and operating clock frequency of last single-core processors (Ref. 12). A — Fan and heat-sink: Celeron D 2.40 GHz; B — pulses of liquid N_2: Celeron D, 2.40 GHz; C — fan and heat sink: Pentium 4 3.60 GHz; D — pulses of liquid N_2: Pentium 4, 3.60 GHz. Operation clock frequency of device and its voltage increased in BIOS. Heat output of each device increased at a rate greater than operating clock, and the device experienced increased Joule heating and exhibited greater thermal resistance. Control: aluminum heat sink cooler containing six copper heat pipes, primary forced convection part being 120 × 120 × 20 mm fan, Windows® XP run.

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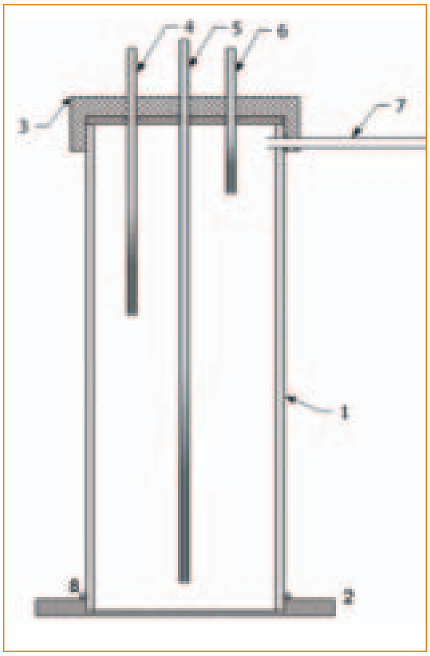

Fig. 2 — Evaporator design. The cold plate at the bottom contacts the cooled surface. This design assumes automated supplying of refrigerant by a temperature-monitoring controller (Ref. 12). 1 — Aluminum cylinder, 2 — Sterling silver cold plate, 3 — Soldered lid, 4 — Thermocouple input, 5 — Liquid N_2 supply tube, 6 — Vapor output, 7 — Vapor distribution tube, 8 — Solder joint.

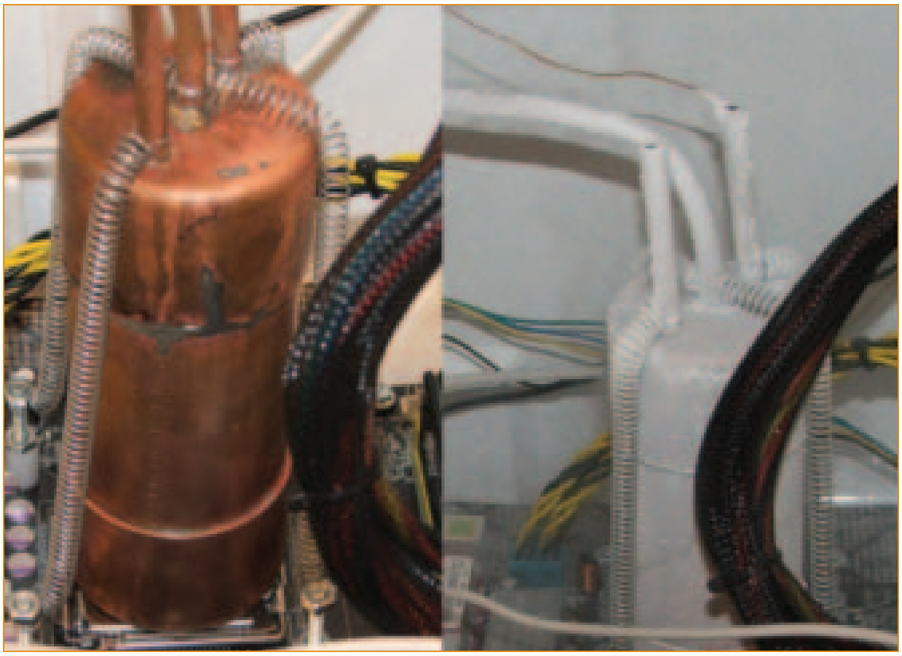

Fig. 3 — Computer installed within automated refrigeration system, wherein liquid N_2 is the working fluid. The Cu evaporator is pictured (Ref. 12).

Dissipating Heat

Heat spreaders subject to free air convection can conduct heat away from a contacted surface. To dissipate greater heat loads, their surface area must either be increased linearly or exposed to greater airflow (Ref. 5). Larger heat-sinks predominantly utilize forced air convection parts, and contain technologies facilitating greater rates of internal heat transfer such as heat-pipes, which are elements wherein heat is transferred between two ends of a sealed chamber by a liquid that is evaporated at one end to condense passively at the other (Ref. 6). Software throttling in response to heating or net computational workload exists (Ref. 7). However, the next big step has been debated.

Advances in Technology

Contemplated leaps to technologies, which manage the concentrated dynamic heat-loads expected in the near future, all assume wider use of mediums other than air, such as working fluids like water, low-boiling-point refrigerants, low-melting-point alloys, and cryogens. Water has a higher thermal effusivity and volumetric thermal capacity than air (0.16 W/cm^2/K/s$^{0.5}$ and 4.185 J/m^3·K·10^6, respectively, at 60°C). Systems utilizing liquid alloys of sodium or gallium pumped by electromagnets are even more favorable in this regard (Refs. 8, 9). Water may be released upon a surface by small jet arrays in quantities such that its boiling removes as much as 1000 W/cm^2 from the surface. Refrigerants such as chlorodifluoromethane and tetrafluoromethane boil at lower temperatures (Refs. 10, 11). Technologies exist that allow for as much as 100% increases in the operating clock frequency of modern computing devices, or comparatively yielding changes in device complexity — Figs. 1 and 2.

However, producing marketable solutions requiring a relatively high level of capital investment on the part of consumers involves satisfying the related objectives of 1) eliminating hassle and service costs related to minimum maintenance by increasing the life cycle of relevant parts, and 2) increasing the marginal benefits of the technologies over standard fare. The latter function can be achieved either by decreasing net cost through use of less expensive materials, or increase efficiency through use of more expensive materials. To avoid contradiction, designs of many materials are unavoidable.

One component that must necessarily be resolved in this manner is the refrigerant evaporator, which is applied to the cooled surface of the CPU in most low-temperature refrigeration systems. This part experiences significant thermal cycling, and while aluminum is preferable in this respect as a lightweight metal, as well as in material cost relative to copper, its poor thermal conductivity relative to copper and silver make it only suitable as part of the construction. The most cost-efficient configuration of materials to comprise an evaporator suitable for operation at 77K (the boiling point of the most inexpensive refrigerant, liquid nitrogen) is an A3003 body soldered to a sterling silver cold plate, which contacts the device being cooled and is the intermediate surface between heat load and working fluid — Fig. 3.

In previous work, a copper evaporator was used. It was placed at the surface of the central processing unit, while other components are cooled at different local temperatures within specific areas of the sealed subenvironment through automated refrigerant flow in prearranged tubing coils. Air condensation was prevented by enclosing all computer components in a sealed subenvironment wherein air was pumped out. As liquid nitrogen evaporated, it was circulated through this chamber (Ref. 12). Noncryogenic applications can also benefit from similar material combinations (Ref. 13).

Investigating Base Metal/Solder Combinations

The objective of this work was to gather the following data for copper or aluminum base metal/solder combinations: 1) Tensile strength of base materials before and after cryogenic cooling; 2) shear strength of soldered joints after soldering and after cryogenic cooling; and 3) microstructure analysis of soldered joints after soldering and after cryogenic cooling.

Conducting the Experiment

Copper C1010, sterling silver, and aluminum Alloy A3003 in the form of wrought tube and sheet were used as the base materials with the lead-free solder Sn-20 wt-% Zn. Standard single-lap shear test specimens of all these materials were manufactured according to specification AWS C3.2M/C3.2:2008* (Fig. 2 at the overlap 0.24 in. [6 mm]).

Prior to assembly of the joint, faying surfaces were cleaned with fine sandpaper and ethyl alcohol before soldering. Copper-to-silver joints were soldered with the acidic flux No. 71 supplied by Superior Flux Mfg. Co., Cleveland, Ohio. In order to join aluminum to silver, both base metal faying surfaces were pretinned with the Sn-20Zn solder by rubbing with a steel brush on the hot plate. Then, aluminum-to-silver joints were soldered without an additional solder portion but using the organic aluminum soldering flux ASF-40 (Ref. 14) supplied by Titanium Brazing, Inc., Columbus, Ohio.

Soldered joints were subjected to cryogenic cooling by submerging them into liquid nitrogen. Specimens were dipped into liquid nitrogen and held for 6 min to provide full cooling to the temperature –196°C. Following each cryogenic cooling, the specimens were dipped into water to return them to room temperature. The base materials were subjected to the same cryogenic treatments as joined specimens.

The specimens were subjected to tensile testing to determine ultimate shear strength of joints and tensile strength of base materials.

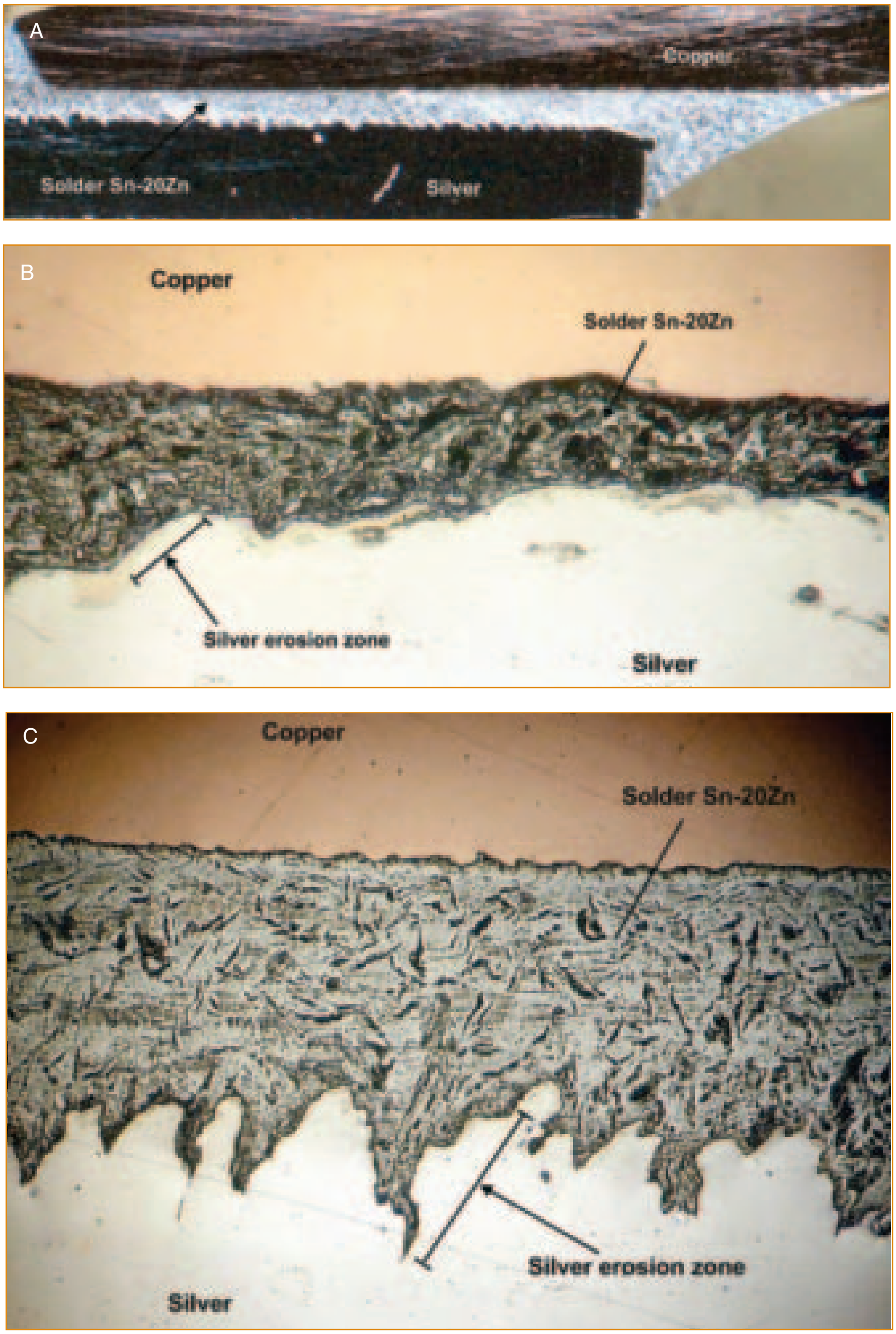

Fig. 4 — Structure of copper-silver soldered joints. A — Macrostructure after soldering, 2×; B — microstructure after soldering, 100×; C — after cryogenic treatment, 100×.

Results of the Investigation

Mechanical Properties

The results of the mechanical testing of base metals and soldered joints are presented in Table 1. The data in Table 1 are comprised of averages from the performance of 4–7 specimens tested for each combination of base metals.

The repeated cryogenic cooling does not affect tensile strength of copper and A3003 alloy unless another thermal treatment was done before contacting liquid nitrogen. After soldering, base metals that were subjected to cryogenic thermal cycling had a significant decrease in tensile strength by approximately 15% for

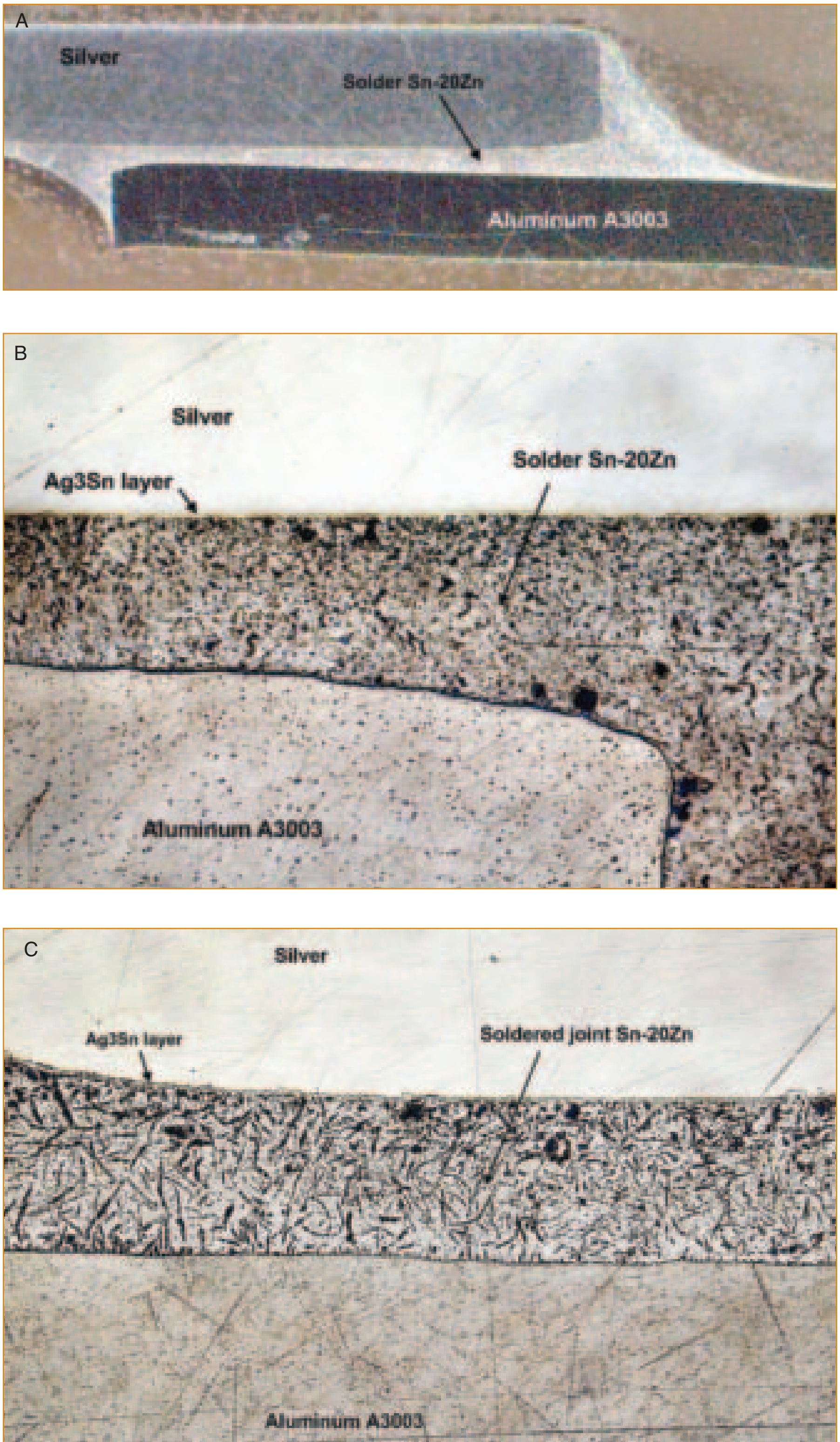

Fig. 5 — Structure of aluminum-silver soldered joints. A — Macrostructure after soldering, 2×; B — microstructure after soldering, 100×; C — after cryogenic treatment, 100×.

both aluminum and copper. This means that short-term heating during soldering to 270°–300°C (520°–570°F) affects the base metal strength more adversely than short-term thermal cycling at cryogenic temperatures.

The cryogenic thermal cycling decreased shear strength of aluminum-silver soldered joints by 14%, whereas the strength of copper-silver soldered joints was changed insignificantly — only by 4%. No cracks or microcracks were found in joints after soldering; therefore, a slight decrease of mechanical properties was accepted as noncritical for the application in electronics cooling, where structured soldered joints are not exposed to any stresses other than those arising from dissimilar expansion/contraction of joint materials during thermal cycling.

Microstructure of Soldered Joints

Microstructures of copper-silver joints soldered with the Sn-20Zn solder are presented in Fig. 4. The joint metal is dense, without voids and pores. Despite the formation of Ag_3Sn intermetallics was expected at the interface between silver base and solder, no intermetallics were found. However, the joints were characterized with significant erosion of silver by the solder — Fig. 4B, C. The joint microstructure was changed after cryogenic cooling. A eutectic type of solder microstructure after soldering was transformed into a quenching-type microstructure after on-and-off cryogenic cooling. This change did not result in a shear strength gain due to significant tin content in the solder, which causes low strength of the alloy independent of any structural changes.

Microstructures of aluminum-silver joints soldered with the Sn-20Zn solder are presented in Fig. 5. The joint metal is dense, without voids but with several small-size pores (Fig. 5B), which probably appeared due to organic flux application. This flux is characterized by considerable evaporation of gaseous products from the decomposition of organic amines. An expected intermetallic layer of Ag_3Sn phase was found at the silver-solder interface contrary to the previousley mentioned microstructure of copper-silver joints. This can be explained by the fact that silver was pretinned before soldering with aluminum, while soldering of silver with copper was conducted in one thermal cycle.

The cryogenic treatment also trans-

Table 1 — Effect of Cryogenic Treatment on Strength of Base Metals and Soldered Joints

Sample	Base metal at room temperature, MPa	Base metal, 6 min dipping in liquid nitrogen, MPa	Base metal after soldering, 6 min dipping in liquid nitrogen, MPa	Joint at room temperature, MPa	Joint, 6 min dipping in liquid nitrogen, MPa
Aluminum Alloy A3003	**169.2–176.6** **174.7**	**162.2–175.1** **172.6**	**147.7–150.1** **149.5**		
Copper 1010	**271.4–279.1** **276.0**	**273.6–283.1** **281.75**	**229.9–237.4** **234.45**		
Aluminum + Silver + (Sn-20Zn) Solder				**28.2–34.3** **31.63**	**26.3–29.7** **27.32**
Copper + Silver + (Sn-20Zn) Solder				**33.1–38.3** **37.36**	**32.8–36.1** **35.77**

formed the joint microstructure: needle-like structural aspects appeared as distinguishing features of a quenching structure. However, no cracks or microcracks were found in both the copper-silver and aluminum-silver soldered joints after cryogenic treatment. It is possible that thermal stresses are relaxed by relatively soft, plastic tin-zinc solder metal, as well as all the base metals, which also have good plasticity.

Conclusions

Soldered joints of A3003 and silver can be implemented, and are preferable in environments wherein they are expected to experience significant thermal-cycling-induced stress. The implication is that high-efficiency, low-cost components in electronics cooling can be assembled and applied, without a reduction in part life cycles, to intensive heat electronics cooling applications. Heat dissipation solutions dependent upon the relevant constructs are thereby made more competitive and brought nearer to market viability.

Cryogenic cooling resulted in a decrease in tensile strength for both copper and aluminum by about 15%, as well as shear strength reduction of soldered joints, but this can be considered as not critical or dangerous for this application. No cracks were found.

Significant erosion of silver by the Sn-20Zn solder was found after soldering with copper, while a formation of Ag_3Sn intermetallic layer, due to pretinning, prevented this erosion when silver was soldered to aluminum.

Also, the cryogenic treatment resulted in changes in the solder joint microstructure, namely, an appearance of needle-like crystals characteristic of any quenching structure.

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References

1. 2006. 30 Years of computer technology. *NASA Tech Briefs* 30(12).

2. Ashengi, M., and Liu, W. 2007. Microscale heat transfer. *Electronics Cooling* 13(1): 18–23.

3. Ellsworth, M., and Simons, R. 2005. High powered chip cooling – air and beyond. *Electronics Cooling* 11(3): 14–22.

4. Moore, G. 2003. No exponential is forever… We can delay 'forever.' *International Solid State Circuits Conference*.

5. Wilson, J., and Guenin, B. M. 2005. Cooling solutions in the past decade. *Electronics Cooling* 11(4).

6. Yu, M., Cheng, C., Lin, C., and Chen, C. 2007. Heat dissipation module and heat pipe thereof. U.S. Patent Appl. Publ. No. 2007/0102143.

7. Pollard, L. L., and Gupte, N. B. 2006. Dynamic thermal management for integrated circuits. U.S. Patent No. 7,050,959.

8. Li, T., Lu, Y., Liu, J., and Zhou, Y. 2006. A powerful way of cooling computer chip using liquid metal with low melting point as the cooling fluid. *Forch Ingenieurwes* 70: 243–251.

9. Ma, K. Q., and Liu, J. 2007. Heat driven liquid metal cooling device for the thermal management of a computer chip. *Journal of Physics D: Applied Physics* 40: 4722–4729.

10. Rowden, B., Selvam, R., and Silk, E. 2006. Spray cooling development effort for microgravity environments. *Space Technology and Applications International Forum*, pp.134–144.

11. Overholt, M., McCandless, A., Kelly, K., Becnel, C., and Motakef, S. 2005. Micro-jet arrays for cooling of electronic equipment. *Proceedings of 3rd International Conference on Minichannels and Microchannels*, pp. 249–252.

12. Shapiro, L. A. 2007. Cryogenic computer system with parallel multiple cooling temperatures. U.S. Patent 7,243,507.

13. Shapiro, L. A. 2007. Modular semi-conservative and self-scaling electronics cooling system. U.S. Patent Appl. No. 11/840,962.

14. Shapiro, A. E., and Shapiro, L. A. 2008. Hybrid flux for soldering aluminum, U.S. Patent Appl. No. 61/194,197.