



Innovative Low-Temperature Solder Alloy and Optimized Convection Reflow Oven Combination to Achieve Up to 25% Energy Savings

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Abstract

LTS mixed powder alloy was designed for (a) lower energy consumption with lower peak temperature of 200–210°C compared to the SAC305 lead-free alloy (96.5% tin (Sn), 3% silver (Ag), and 0.5% (Cu) copper) with a peak of 240–250°C, (b) increased drop shock resistance compared to bismuth/tin (BiSn) low-temperature alloy, and (c) comparable performance to SAC305 alloy for higher service temperatures of 90–130°C and thermal cycling conditions (-40°C/+125°C). Energy Saver Oven-R (Oven-R) was a convection reflow oven specifically designed to minimize energy consumption when compared to a standard reflow oven. Design optimization included (a) fan frequency optimization for good heat transfer, (b) use of special catalyst granules to reduce the pyrolysis temperature (needed to clean the oven contaminants) from 500°C to 350°C and, therefore, reduce the energy consumed, and (c) eliminating tubes used in standard ovens to carry the process gas and the energy associated. Oven-R incorporated multiple catalyst-pyrolysis modules at multiple oven locations to facilitate on-the-spot cleaning, thus minimizing the energy loss. Testing was performed to measure the power consumed by Oven-R in full load mode for an optimized fan frequency of 30Hz, with SAC305 profile (peak temperature of 240°C). An extension of this test was done for LTS alloy on both Oven-R and a standard reflow oven and compared to SAC305 profile. The combination of reflowing the LTS alloy in the Oven-R resulted in a 27% reduction in (a) power consumption/hour (kW), (b) total cost of energy/year (€), and (c) total CO₂ emissions/year (tons), when compared to the SAC305 alloy reflowed in a standard reflow oven.

Introduction

There is a high emphasis on reducing greenhouse gas emissions and eventually moving towards a carbon-neutral scenario. Electronics manufacturing with printed circuit board assembly (PCBA) involves reflowing solder paste to form a bond between the components and the PCB. Reducing the energy consumed by the reflow oven has a direct impact on reduced CO₂ emissions. In addition to quantifying the energy consumed, there is a growing emphasis on the Life Cycle Assessment

(LCA) of a product. LCA involves a cradle-to-grave analysis of the environmental impacts associated with all the stages of a product's life. (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling) [1].

The PCB assembly process predominantly uses Pb-free SAC305 (Sn3Ag0.5Cu) solder alloy that melts at 220°C and needs typical peak temperatures of 240–250°C in standard convection reflow ovens. Lower-temperature solder alloys

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typically melt between 140–190°C with peak temperatures of 170–210°C and consume less oven energy. The choice of the low-temperature solder alloy is based on technical requirements, such as reducing component warpage, addressing the challenge of a large temperature delta, reducing the coefficient of thermal expansion (CTE) mismatch and therefore stresses, step soldering, soldering temperature-sensitive components, and associated reliability requirements [2].

LTS Alloy with Mixed Powder Technology

BiSn low-temperature solder alloy has historically been used for low-cost applications. However, the intrinsic brittleness of Bi restricts the BiSn alloy for critical applications with drop shock requirements [3]. The lower melting point of BiSn at 138°C also limits the service temperature to 80–90°C, which is not ideal for higher reliability automotive and industrial applications. LTS alloy consists of an engineered ratio of Sn- and In-based alloys and is designed to form reliable solder joints at lower peak temperatures of 200–210°C and maintain the remelting temperature > 180°C (mixed powder engineered ratio eliminates any low melt eutectic phases), thus allowing LTS alloy to withstand higher service temperatures. LTS alloy with the SnIn system is intrinsically ductile without the brittleness of Bi solders and exhibits superior mechanical shock resistance [4].

LTS Alloy Reliability

Figure 1 shows the exponentially improved drop shock resistance of LTS (60–80s at 210°C peak temperature) vs. BiSn (170°C peak temperature, 60–80s time above liquidus) vs. SAC305 (245°C peak temperature, 60–80s time above liquidus). Experimental setup: 10 x 10mm OSP ball grid array (BGA) package, 100 x 100mm board, 500mm drop height, 110g steel ball weight.

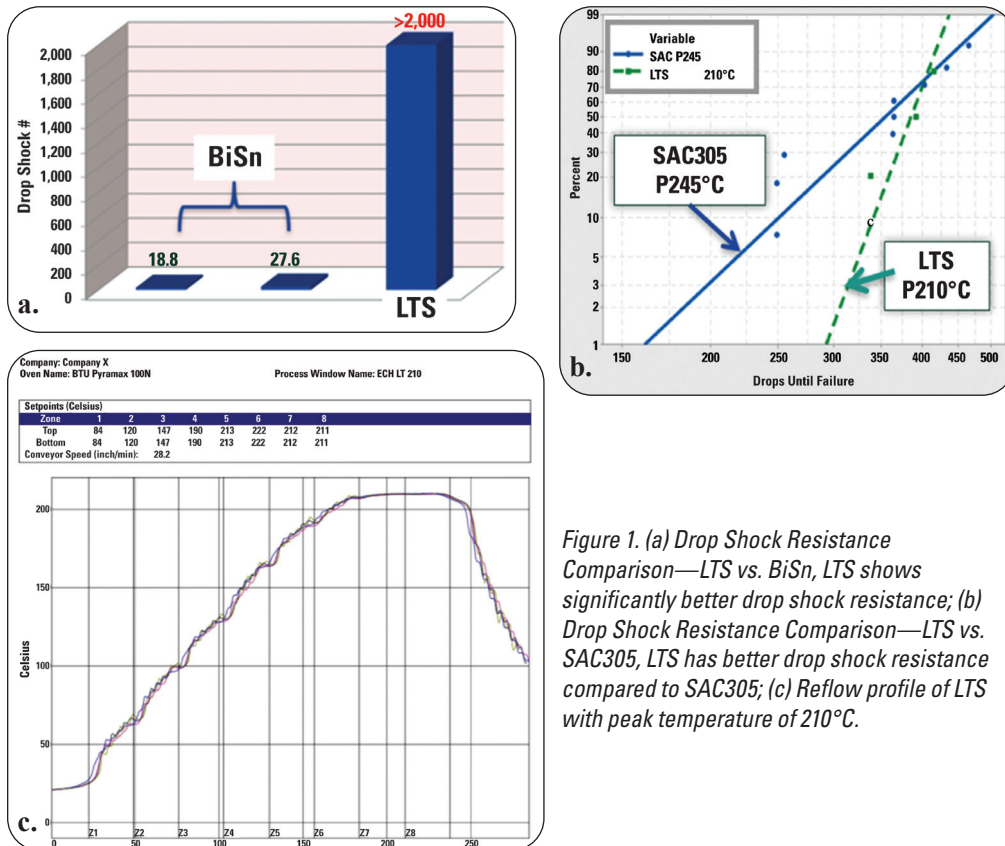


Figure 1. (a) Drop Shock Resistance Comparison—LTS vs. BiSn, LTS shows significantly better drop shock resistance; (b) Drop Shock Resistance Comparison—LTS vs. SAC305, LTS has better drop shock resistance compared to SAC305; (c) Reflow profile of LTS with peak temperature of 210°C.

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Florian Graf is an experienced industrial engineer with over 20 years in the electronics industry, specializing in reflow and vacuum soldering. His expertise lies in optimizing these processes to enhance efficiency and reduce energy consumption, making him a leader in sustainable manufacturing. Florian is known for combining practical experience with deep technical knowledge to improve production quality and implement energy-saving solutions. His commitment to innovation and sustainability has established him as a trusted expert in process optimization within the electronics sector. SMT Thermal Discoveries focuses not only on energy savings, but also on reducing production footprint and minimizing the use of spare parts throughout system lifecycles, ensuring long-term efficiency and sustainability.

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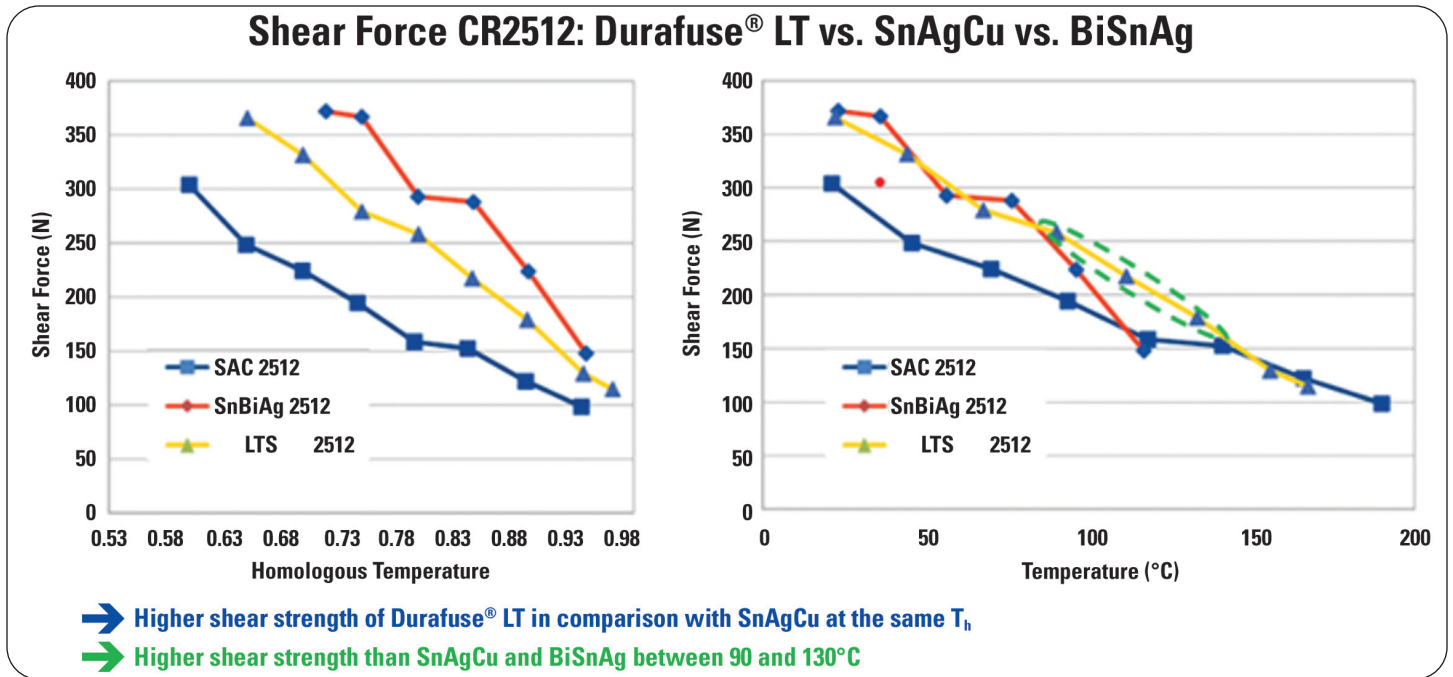


Figure 2. Shear Force Comparison—LTS vs. BiSn vs. SAC alloys for different service temperatures and homologous temperatures. (Source: Dr. Andrej Novikov, Universitat Restock.)

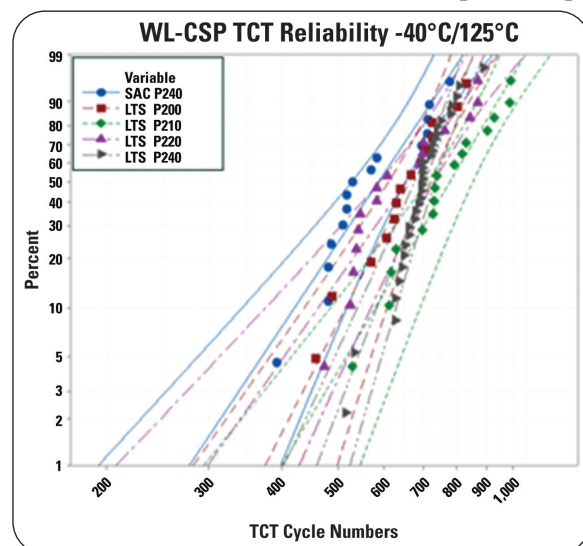
Figure 2 shows the shear force comparison between LTS (60–80s at 210°C peak), BiSnAg (170°C peak, 60–80s time above liquidus (TAL)), SAC305 (245°C peak, 60–80s TAL) for different service temperatures as well as different homologous temperatures (ratio of service temperature to the alloy melt temperature), for a 2512 chip capacitor. LTS exhibited higher shear force than SAC305 and BiSnAg in the 90–130°C service temperature range making it a promising low-temperature candidate for higher reliability applications such as automotive and industrial electronics. LTS and Bi/Sn/Silver (Ag) alloys had higher shear force compared to SAC305 at the same homologous temperatures.

For thermal cycling reliability (-40°C/+125°C, 20min dwell, 65min/cycle), a wafer-level chip-scale package (CSP) (wafer-level packaging WLP256, full-array, 0.25mm diameter SAC305 balls and 0.4mm pitch) when assembled with SAC305 paste experienced failures at the wafer bond

Alloy	Characteristic Life (cycles)	Slope	First Failure
SAC305 @ 240°C	625.8	5.7	392
LTS @ 200°C	697.2	7.4	457
LTS @ 210°C	824.5	6.4	529
LTS @ 220°C	701.9	5.4	473
LTS @ 240°C	730.9	9.9	516

Figure 3. Wafer-Level Package; characteristic life when assembled with LTS @ 210°C comparable to characteristic life when assembled with SAC305 @ 240°C.

pad-solder interface. LTS alloy as solder paste was tested as a potential replacement to SAC305 paste, as it was expected that the higher ductility of LTS joints would absorb more stress/strain energy under cycling and increase the lifetime to failure (failure defined as electrical resistance increase by 100%). Figure 3 shows the Weibull plot on the thermal cycling results of the WLP256 CSP assembled with SAC305 paste reflowed at a peak temperature of 240°C vs. LTS alloy reflowed at different peak temperatures of 200°C, 210°C, 220°C, and 240°C. LTS alloy showed improvement in both the characteristic life and the first failure by at least 10% compared to SAC305, in all cases of the different peak temperatures [5].



Reduced Oven Contamination (Induced by PCB Solder Mask Outgassing) With LTS Alloy

The PCB solder mask typically contains melamine (1,3,5-Triazine-2,4,6-Triamine). This can outgas at higher temperatures and cause oven contamination. In one particular instance with a large PCB form factor and a high solder mask content, coupled with the high frequency of boards reflowed with SAC305 alloy (240–250°C peak temperature), significant oven contamination could be seen in the oven heating zones and cooler coils. This resulted in very frequent

cleaning that led to downtimes of 4 hours/week. It was originally thought that the oven contamination was from the flux residue of the SAC305 solder paste (reflowed at a peak temperature of 240–250°C). Fourier Transform Infrared Spectroscopy (FTIR) analysis of the oven contamination and flux residue showed no chemical match, but there was a clear match in the FTIR signature of the oven contamination and the melamine in the PCB solder mask. Figure 4 shows the contaminant in the oven and the FTIR spectrums of the oven contaminant, melamine (1,3,5-Triazine-2,4,6-Triamine), and the SAC305 paste flux residue. The PCB solder mask supplier recommended a lower temperature inside the oven to reduce the outgassing of the melamine from the solder mask. LTS alloy was reflowed on the same PCB at a peak temperature of 205°C. The amount of melamine contamination inside the oven was significantly reduced. Downtime due to the oven cleaning was reduced from 4 hours to less than 30 minutes/week.

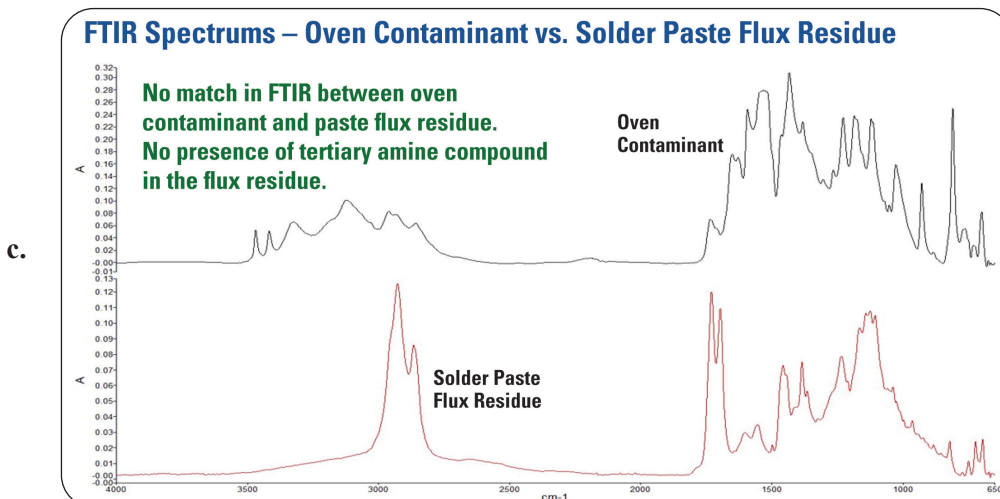
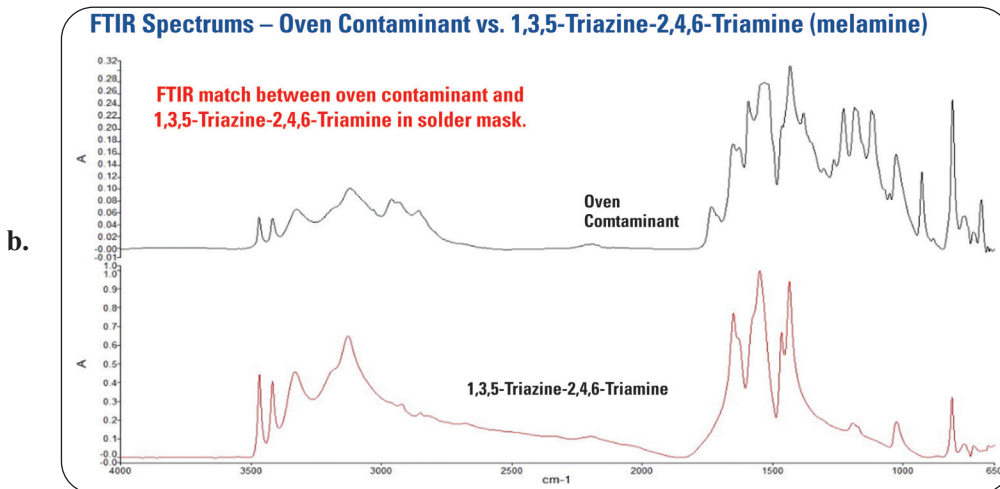


Figure 4. (a) Oven contamination due to melamine (1,3,5-Triazine-2,4,6-Triamine) outgassing from the solder mask; (b) FTIR spectrum analysis showed a match between contamination in the oven and melamine present in the PCB solder mask; (c) FTIR spectrum analysis showed no correlation between the solder paste flux residue and the contamination in the oven.

Convection Reflow Oven-R: Design Optimization for Reduced Energy Consumption

A convection reflow oven provides heat energy to the solder alloy to melt and form a reliable solder joint between the component and PCB. Heating the oven system is the most energy-intensive part of the process. Depending on the profile and the individual product requirements, the heating phase could consume 50kWh–80kWh. To reduce the overall energy consumed, the following design optimizations were specifically incorporated in Oven-R.

Oven-R: Optimized Fan Frequency for Good Heat Transfer

Once the oven system has reached the desired temperature, a large part of the energy consumed is to power the oven fans that facilitate heat transfer to the PCB assembly. For an oven heating zone length of 3.6m, optimized fan frequencies help reduce the energy consumed by up to 20%.

Oven-R: Insulation Optimization

Improved insulation can significantly reduce heat loss to the outside environment. At the same time, too much insulation will prevent individual heating zones from reaching the individual set temperatures and instead heat all zones to the same temperature. For an oven heating zone length of 3.6m, improved insulation helps achieve average energy saving of 1kWh.

Oven-R: Catalyst-Aided Pyrolysis for Reduced Energy Consumption

During reflow, long-chain hydrocarbons are released and condense in condensate traps in the oven, causing resinous/oily contamination. To address this contamination, pyrolysis is used to burn the contaminants at temperatures of up to 500°C. In standard ovens, the process gas with contaminants is transported by tubes to a chamber at the end of the oven where pyrolysis happens. Energy is therefore consumed for the actual pyrolysis as well as transporting the process gases through tubes. With the optimized Oven-R, multiple designs are incorporated to lower energy consumption. The use of special catalyst granules accelerates the chemical reaction of breaking the hydrocarbon chains and helps reduce pyrolysis temperatures from 500°C to 350°C, thus reducing energy consumed. Tubes are also eliminated, thereby eliminating the energy needed to transport process gases. Instead, there are multiple catalyst-pyrolysis modules where gas from the process chamber is pulled through heated catalyst granules

at multiple locations in the oven for on-the-spot cleaning, and reintroduced back into the chamber, with minimal energy loss. Figure 5 shows the schematic of the Oven-R configuration and the mechanism of the catalyst-pyrolysis module. Circulating the process gas over large surfaces of the catalyst granules also substantially reduces oven contamination. Figure 6 shows the reduced contamination in the inlet condensate trap with catalyst granules vs. without the catalyst. This was for a period of 6 weeks: 3 shifts/day, 5-day week.

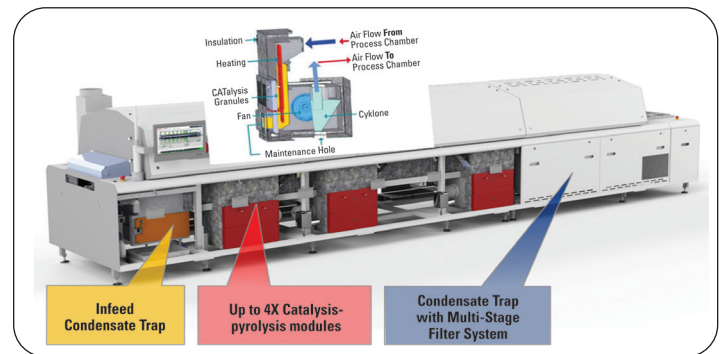


Figure 5. Energy Saver Oven-R configuration with the catalyst-pyrolysis modules to minimize energy loss.

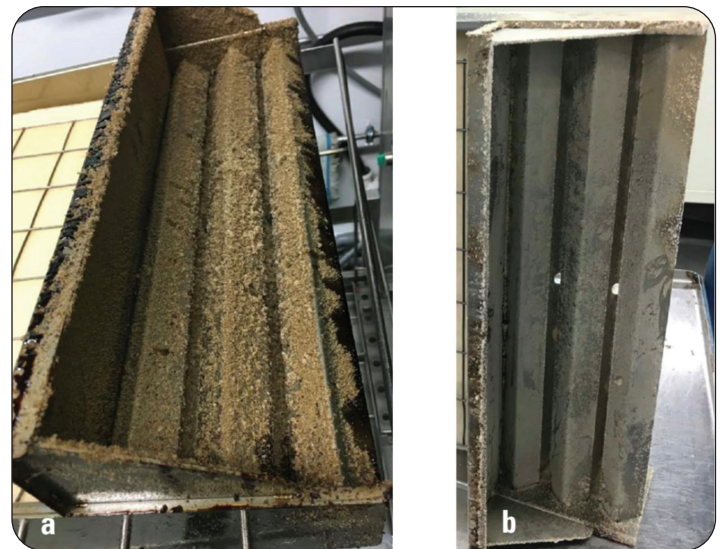


Figure 6. (a) More contamination without catalyst granules; (b) significantly less contamination with catalyst granules.

Experimental Setup to Measure Energy Consumed by Oven-R

To ensure neutrality, an internationally recognized independent standards organization measured the energy consumed for a SAC305 profile in the optimized oven that was specifically designed to consume less energy.

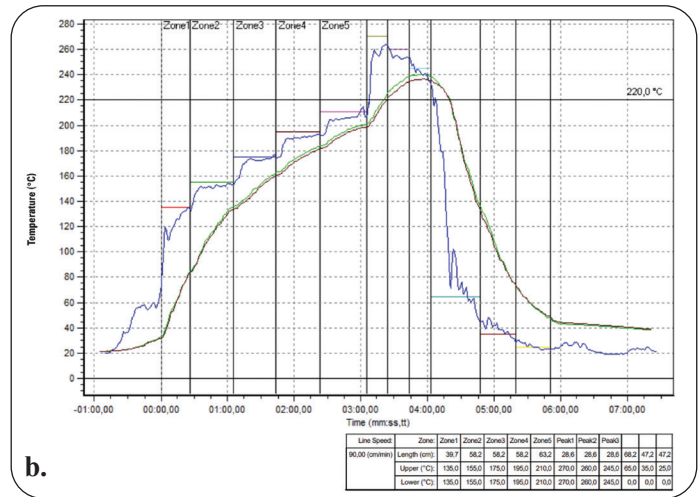
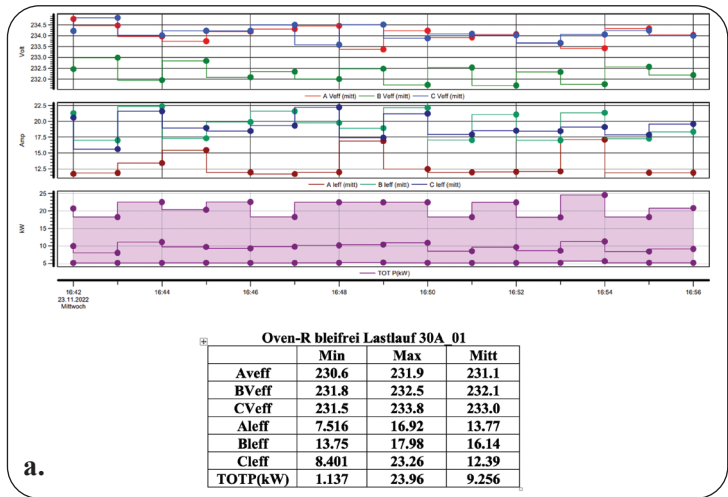
To simulate a fully loaded oven, Aluminum boards (220 x 235 x 2mm) were used in Oven-R with oven heating zone length of 3.6m, and a cycle time of 32 seconds. Oven-R was run in full load mode at 30Hz optimized fan frequency. Table 1 shows the power consumption (minimum, maximum, average) in the full load mode. Measurements under full load lasted approximately 15 minutes. Figure 7 shows the measured power consumption plot for full load mode at 30Hz and the profile temperature. A power analyzer and current transformer were used for the power measurements as per EN50160, EN61000-4-15 standards. The instrument deviations (error limits) were first verified in relation to the measurement ranges used. Table 2 shows the measured deviation of the instruments.

Table 1. Power consumed by Oven-R at 30Hz fan frequency for full load.

Operating Mode	P _{min}	P _{max}	P _{average}
Full load mode: 30Hz fan frequency	1.137kW	23.96kW	9.256kW

Table 2. Measured Instrument Deviation in TÜV SÜD testing.

Measurement Device	Serial Number	Measured Variable	Measurement Range	Inaccuracy
Mavowatt 20	QS-004 04549	voltage eff current eff nominal frequency PF (Cos φ)	1...6000V 5...6.000A 42,5...57.5Hz 0...1	±0.1% ±0.1% ±0.01Hz ±0.1%
Flexible Current Transformer Dranflex 3003XL	F11040376052 F11040374052 F11040376952	Voltage Voltage Voltage	300/300/3.000A 300/300/3.000A 300/300/3.000A	±0.1A ±0.1A ±0.1A



Probe	Reflow Results					
	Positive Slope (°C/Sec)	Rise Time (150.0 - 200.0°C) (mm:ss,tt)	Time Above Liquidus (220.0°C) (mm:ss,tt)	Peak Temperature (°C)	Delta T (°C)	Negative Slope (°C/Sec)
#1 (°C)	1.80	01:35.00	00:50.00	231.1	25.1	-3.92
#2 (°C)	2.00	01:37.00	00:52.00	233.0		-4.10
#3 (°C)	4.82	01:30.00	00:58.00	256.2		-13.55

Figure 7. (a) Power consumption plot for Oven-R run at full load @ 30Hz fan frequency for a SAC305 profile with a peak temperature of 240°C; (b) average power consumed was 9.256kW; (c) SAC305 reflow profile use with peak temperature of 240°C.

Energy Consumption Comparison – LTS Alloy vs. SAC305 Alloy; Standard Reflow Oven vs. Oven-R

An extension of the test was conducted to include LTS alloy and quantify the power consumed. LTS alloy profile (Peak temperature at 205°C) was compared against SAC305 alloy profile (Peak temperature at 240°C) in two different ovens: (a) standard convection reflow oven, and (b) Oven-R.

Aluminum boards (220 x 235 x 2mm) were used to simulate full load mode in both ovens. Both ovens had a heating zone length of 3.6m with fan frequency set at 30Hz. Oven stabilization took 10 minutes from the time the ovens were switched on. This was followed by 120 minutes of keeping the oven in the steady state. Oven pre-loading took 10 minutes. Power consumption measurements were then taken for 30 minutes.

Table 3 compares (a) the power consumption/hour (kW), (b) the total cost of energy/year (€), and (c) the total CO₂ emissions per year (tons), for both LTS solder alloy and SAC305 alloy, processed in the standard reflow oven and the Oven-R. The cost of energy at 0.25 €/kW was based on the German energy tariff. The CO₂ equivalent of 410g/kWh was based on Germany’s Federal Environmental Agency’s (UBA) numbers for 2022 [6]. The cost of energy/year was calculated by multiplying the power consumed (kW) x cost/kW (€) x operating hours/year. The total CO₂ emissions per year were calculated by multiplying the power consumed (kW) x CO₂ equivalent (g/kWh) x operating hours/year.

The combination of the LTS alloy (peak temperature at 205°C) and the Oven-R consumed the least energy of 7.2kW/h. This number was 27% lower than the power consumed by the SAC305 alloy (peak temperature equals 240°C) reflowed in a standard oven. The LTS alloy and Oven-R combination automatically also resulted in a 27% reduction in the total cost of energy consumed/year and a 27% reduction in the total CO₂ emissions/year.

Table 3. Compares both LTS solder alloy and SAC305 alloy; processed in the energy saver Oven-R and the standard reflow oven, for (a) Power Consumed/hour (kW); (b) Energy Cost/year (€); (c) Total CO₂ Emissions per year (tons); (d) LTS solder along with Energy Saver Oven[®] resulted in a 27% reduction in power consumption/hour, energy cost/year, and total CO₂ emissions per year; (e) operating metrics used for the calculations below.

a.

Power Consumption / hour (kW)	Standard Reflow Oven	Energy Saver Oven-R
SAC305 alloy	9.9kW	8.8kW
LTS alloy	8.84kW	7.2kW

b.

Energy Cost / year (€)	Standard Reflow Oven	Energy Saver Oven-R
SAC305 alloy	€ 14.895	€ 13.200
LTS alloy	€ 13.260	€ 10.800

c.

Total CO ₂ Emissions / year (tons)	Standard Reflow Oven	Energy Saver Oven-R
SAC305 alloy	24.4 tons	21.6 tons
LTS alloy	21.7 tons	17.7 tons

d.

LTS low-temperature alloy reflowed in Energy Saver Oven-R vs. SAC305 alloy reflowed in a standard reflow oven	
Measured Power Consumption/hour (kW)	27% reduction in (a) Power Consumption/hour (b) Energy Cost/year (c) Total CO ₂ Emissions/year
Energy Cost/year (€)	
Total CO ₂ Emissions/year (tons)	

e.

Operating hours/day = 24 Operating days/year = 250 Operating hours/year = 6,000

Energy Cost (based on German Energy Tariff) = 0.25€/kW CO ₂ Calculations Based on Germany’s Federal Environmental Agency (UBA) calculations, the specific carbon dioxide emission factor for 2022 —based on preliminary data = 410g/kWh— https://www.umweltbundesamt.de/das-uba/wer-wir-sind
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Summary

The LTS mixed powder alloy technology demonstrated its ability to (a) form a reliable solder joint at lower reflow temperatures of 200–210°C compared to the SAC305 alloy with a peak of 240–250°C, (b) achieve exponentially increased drop shock resistance compared to the BiSn alloy, (c) be comparable/better than SAC305 alloy for thermal cycling conditions of -40°C/+125°C, and (d) reliably operate at higher service temperatures of 90–130°C. The LTS alloy also significantly reduced oven contamination due to melamine (present in the PCB solder mask) outgassing when compared to the SAC305 reflow where the melamine outgassing was much higher due to the higher peak temperature.

The convection reflow Oven-R incorporated several design optimizations to minimize power consumption. The fan frequency was optimized for efficient heat transfer and reduced the energy consumed by up to 20%. The oven insulation was optimized to achieve average energy savings of 1kWh. A unique catalyst-pyrolysis module was designed to use catalyst granules to accelerate the chemical reaction of breaking the hydrocarbon chains of the oven contaminants and reduce the pyrolysis temperature from 500°C to 350°C, thus reducing energy consumed. Standard reflow ovens use tubes to transport process gas for pyrolysis. Oven-R eliminates these tubes and the energy needed to transport the process gas. Instead, there are multiple catalyst-pyrolysis modules where gas from the process chamber is pulled through heated catalyst granules at multiple locations in the oven for on-the-spot cleaning, and reintroduced back into the chamber, with minimal energy loss.

An independent standards institute performed baseline testing of the power consumption per hour (minimum, maximum, and average power) by the Oven-R run in full load mode (simulated by aluminum boards), for an optimized fan frequency of 30Hz, for a SAC305 profile (peak temperature at 240°C).

An extension of this test was conducted to include LTS alloy and quantify the power consumed. LTS profile reflowed at a peak temperature of 205°C, was compared to the SAC305 profile reflowed at a peak temperature of 240°C. Both the alloys were reflowed in two different ovens: (a) standard convection reflow oven, and (b) Oven-R. Aluminum boards were again used to simulate full load mode. Power consumption per hour (kW) was measured for both the alloys in both the reflow oven types. This was used to calculate the total cost of energy/year (€) and the total CO₂ emissions/year (tons). The cost of energy at 0.25€/kW was based on the German energy tariff. The CO₂ equivalent of 410g/kWh was based on Germany's Federal Environmental Agency's (UBA) numbers for 2022.

The combination of the LTS alloy and the Oven-R, consumed the least energy of 7.2kW/h. This number was 27% lower than the power consumed by the SAC305 alloy reflowed in a standard oven. The LTS alloy–Oven-R combination automatically also resulted in a 27% reduction in the total cost of energy consumed/year, and a 27% reduction in the total CO₂ emissions/year.

The numbers above have been generated using aluminum boards to simulate full load mode in the oven. PCB assembly in electronics manufacturing uses FR4 printed circuit boards (PCB). The PCB form factor, the overall thermal mass of the PCB plus components, and the volume and frequency of boards reflowed in the oven in production are all variables that will directly impact the energy consumed by the oven. Based on real-life production setups, for medium/high volume assembly manufacturing, FR4 PCB assembled with LTS solder alloy (peak temperature of 205–210°C) and reflowed in the Oven-R, resulted in 15–20% energy savings when compared to FR4 PCB assembly with SAC305 solder alloy (peak temperature of 240–250°C) and reflowed in standard reflow ovens.

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