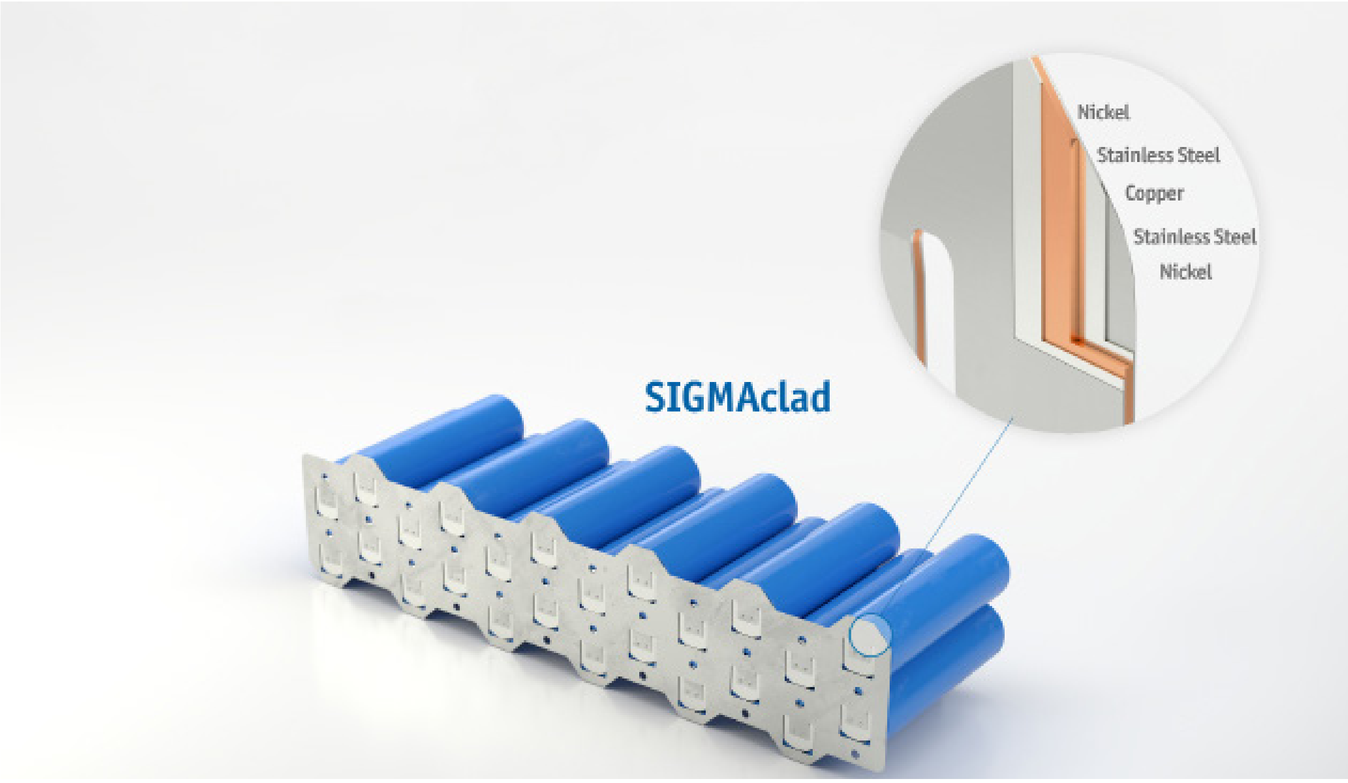
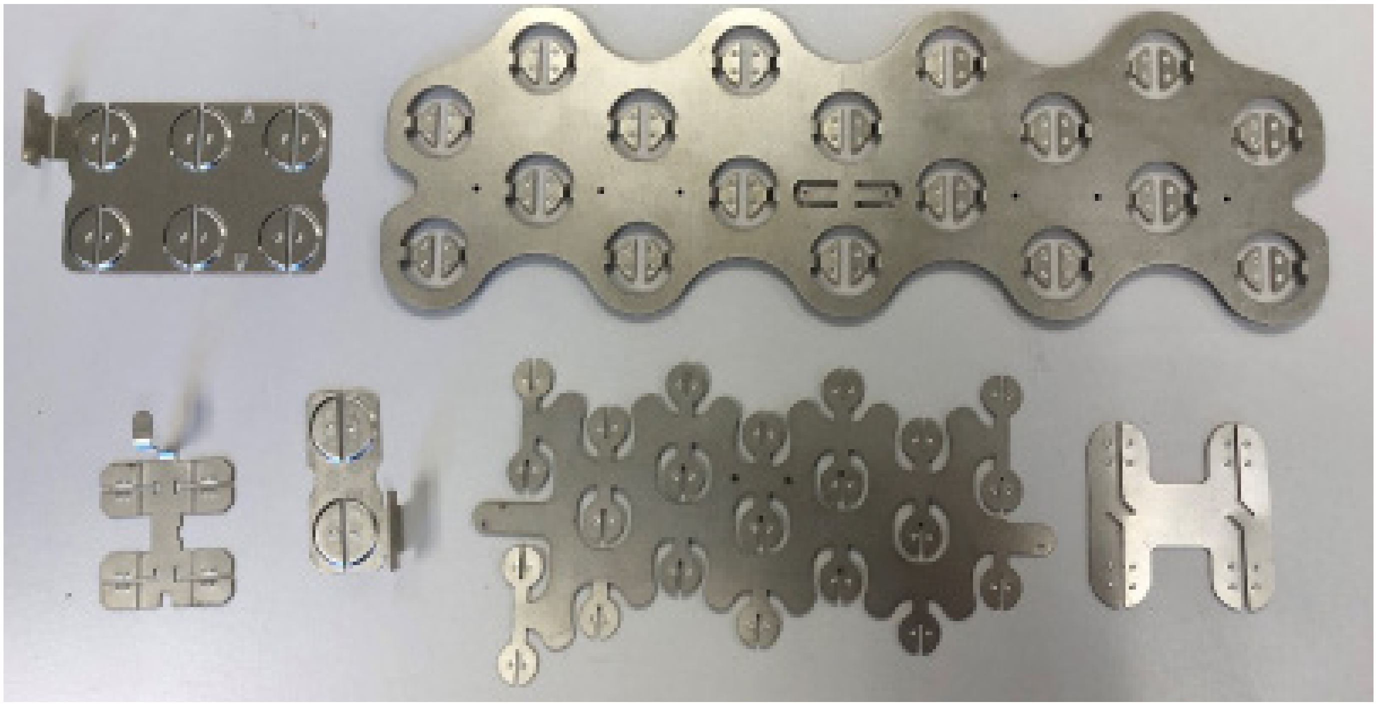
DESIGNERS GUIDE SIGMACLAD®

Engineered Materials Solutions
Wickeder Group

Solving Your Battery Interconnect Challenges!





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SOLVING YOUR BATTERY INTERCONNECT CHALLENGES

At EMS, we produce a variety of "laminated" materials that can offer distinctive properties, where one material alone could not. Most notably, we have developed substitutes for Nickel and Copper Alloys in a multi-layer composite, SIGMACLAD®.

SIGMACLAD® is a 5-Layer clad material composed of Ni/SS/Cu/SS/Ni created specifically for the electrical connection of Li-Ion Battery Packs. It is designed with superior properties compared to other materials used in these applications like Nickel or Nickel Plated Steel.

The Copper layer provides enhanced electrical and thermal conductivity for heat dissipation. The Stainless-Steel layers facilitate resistance welding and increases weld strength. The exterior layers of Nickel allow for easy soldering and provide enhanced corrosion resistance. All these features are provided at a cost that can be lower than pure Nickel and competitive with Nickel Plated Steel.

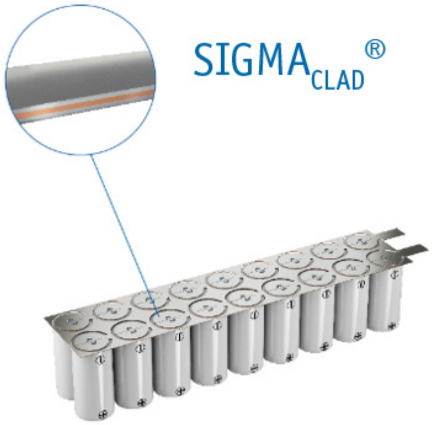
Clad Materials of EMS...
...Get Connected!

Get Started with SIGMACLAD®

A clad material combines two or more metal strips by bonding them together. By bonding different combinations of metals, the advantages of the individual metals are combined into a composite that is tailored to your specific product needs and requirements.

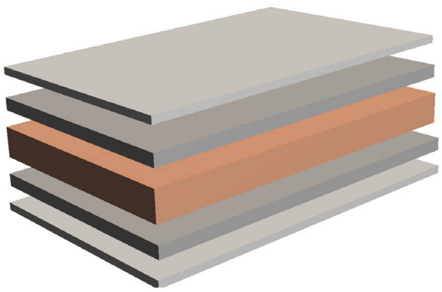
Clad materials are often used to replace nickel or nickel alloys for both cost and performance reasons. Nickel substitute clads are targeting opportunities in the lithium battery industry for both connector tabs and joining plates for multi-cell packs.

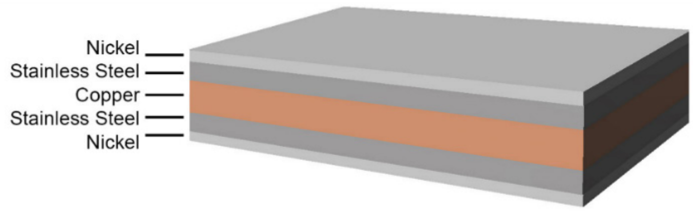
Designated SIGMACLAD®, EMS' 5 layer Ni/S304/C102/S304/Ni system offers an optimum combination of conductivity, solderability, strength, formability, weldability, and corrosion resistance. Improved thermal conductivity is especially important today as the number of individual 18650 cells in a pack increases heat generation, particularly at the bus bar which reduces efficiency of cells and poses a risk of overheating.



Advantages

- Resistance / Laser Weldable
- Solderable surface (no plating required)
- Superior Conductivity to Nickel & Copper Alloys
- Increased Conductivity Enables Gauge Reduction & Performance Improvement
- Nickel Surface Provides High Contact Corrosion Protection
- Stainless steel provides robust welds
- Increased Rigidity
- Scalable copper inner layer to meet application specific requirements





SIGMACLAD® Sizes

SIGMACLAD® 80	SIGMACLAD® 60	SIGMACLAD® 40
0.50mm	0.20mm	0.15mm
	0.25mm	0.20mm
	0.30mm	0.25mm
	0.40mm	0.30mm
	0.50mm	

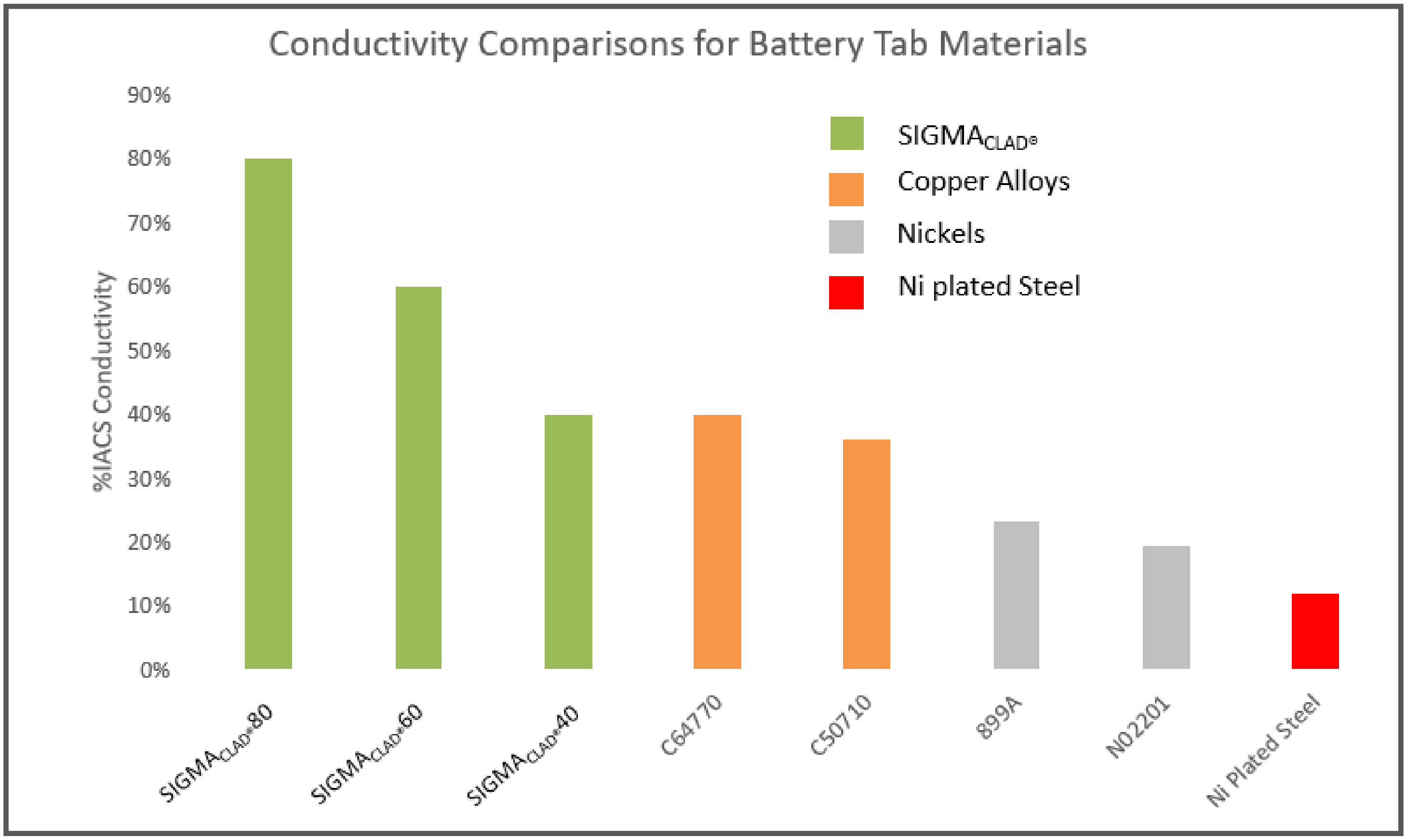
- SIGMACLAD® is available in three ratios corresponding to 40%, 60%, and 80%. IACS depending on electrical and thermal requirements.
- Custom gauges available upon request.
- Width Options: 2.5mm to 580mm

Conductivity and Mechanical Property Comparisons

SIGMACLAD® conductivity is superior to both nickel, nickel plated steel, and copper alloys used for battery tabs.

Electrical Properties @ 20°C (typical properties)	SIGMACLAD®40 Annealed	SIGMACLAD®60 Annealed	SIGMACLAD®80 Annealed	201 Nickel (Annealed)	Ni Plated Steel (AISI 1020)
Conductivity (%IACS) (1)	40%	60%	80%	20%	11%
Resistivity (ohm-m)	4.310×10^{-8}	2.874×10^{-8}	2.155×10^{-8}	8.621×10^{-8}	1.567×10^{-7}

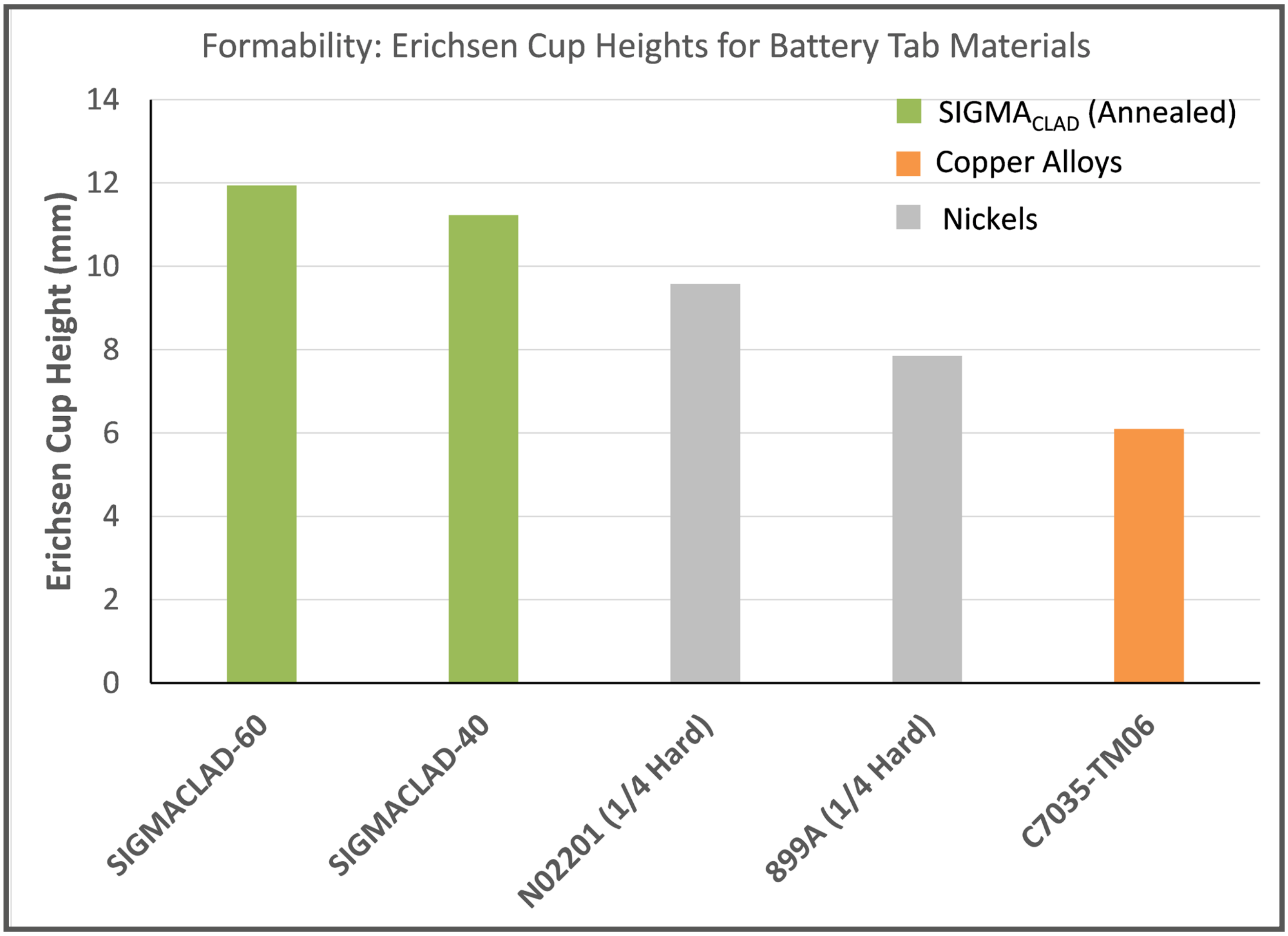
*(1) Properties can vary depending on finish thickness
*(2) Parallel to strip direction
*(3) $\text{SIGMA}_{\text{CLAD}}$®80 mechical propeties based on limited data

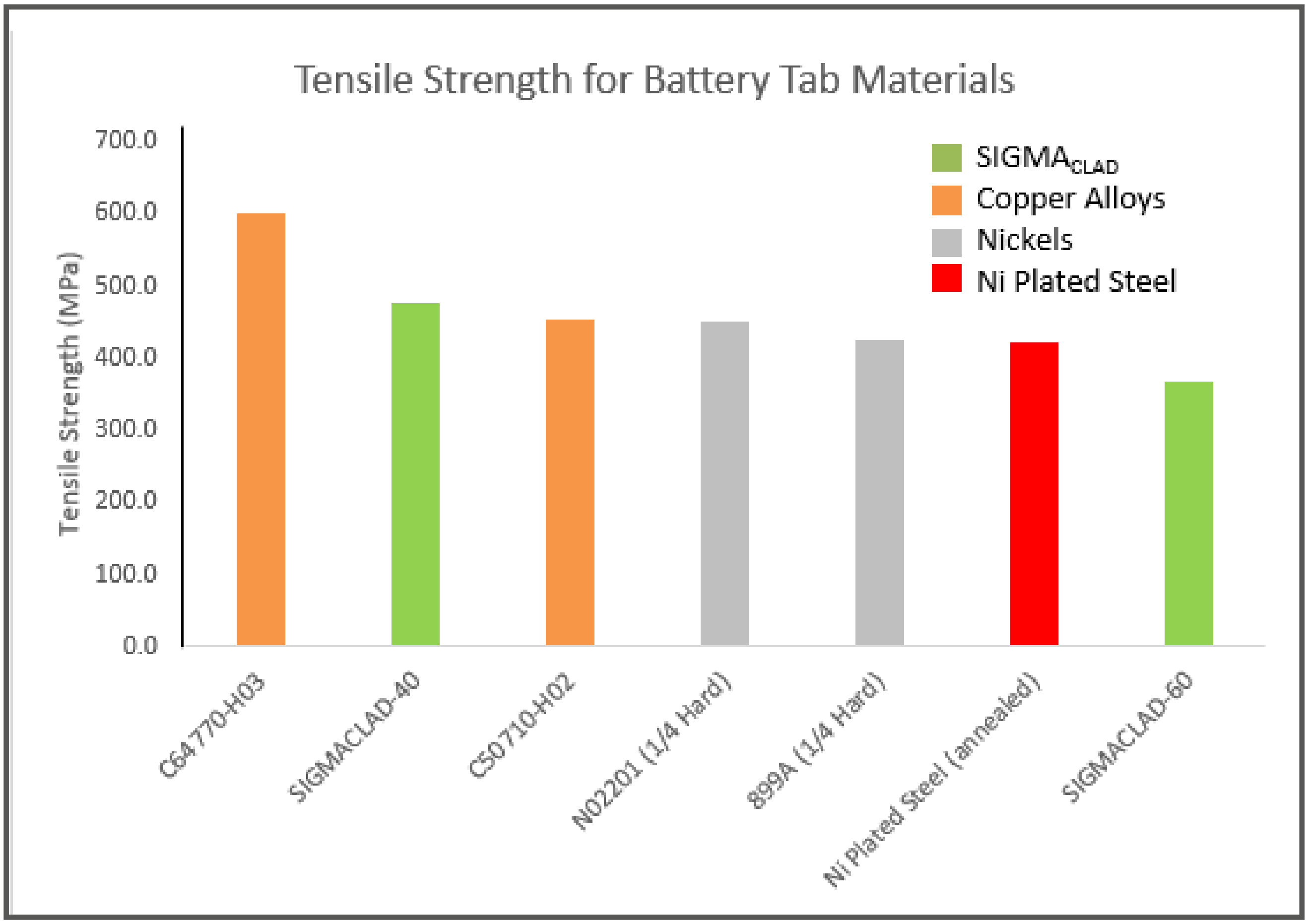


Physical Properties @ 20°C (typical properties)	SIGMACLAD®40 Annealed	SIGMACLAD®60 Annealed	SIGMACLAD®80 Annealed	201 Nickel (Annealed)	Ni Plated Steel (AISI 1020)
Density (Kg/m³)	8,415	8,580	8,666	8,900	7,870
Yield Strength (MPa)	205	138	93	103	350
Tensile Strength (MPa)	475	368	282	414	420
Elongation %	45	48	43	45	15
Erichsen Cup Height (mm)	11.2	11.9	N/A	12.1	N/A
Elastic Modulus (GPa)	165	148	131	207	186
CTE: (µm/m°C)	16.6	16.7	17.1	13.3	11.7
Thermal Conductivity[2] (W/m-K)	178	253	317	79	52
Specific Heat (J/Kg-°C)	447	423	413	456	486

* (1) Properties can vary depending on finish thickness
* (2) Parallel to strip direction

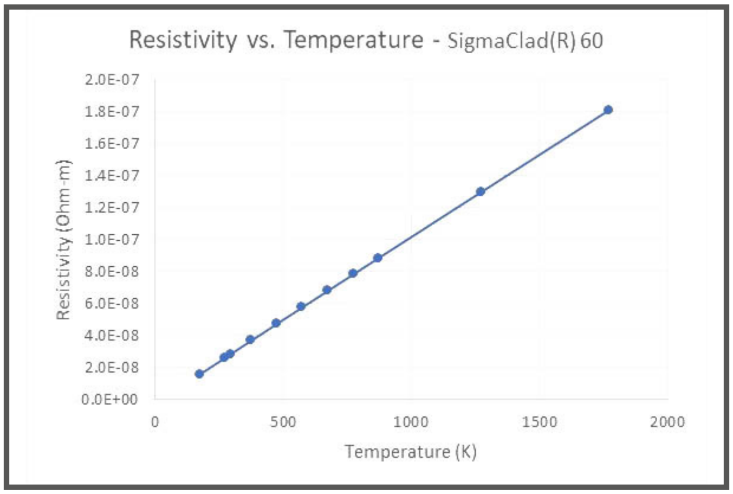
The combination of both tensile strength and elongation is also favorable for SIGMACLAD®. Both tensile strength and elongation exceed ¼ hard nickel strip for the SIGMACLAD ® 40 grade. Due to the higher copper content, the SIGMACLAD® 60 and SIGMACLAD® 80 in the annealed condition have lower tensile strength than quarter-hard nickel. However, the ductility is higher, and similar properties can be achieved with an added small amount of cold work.

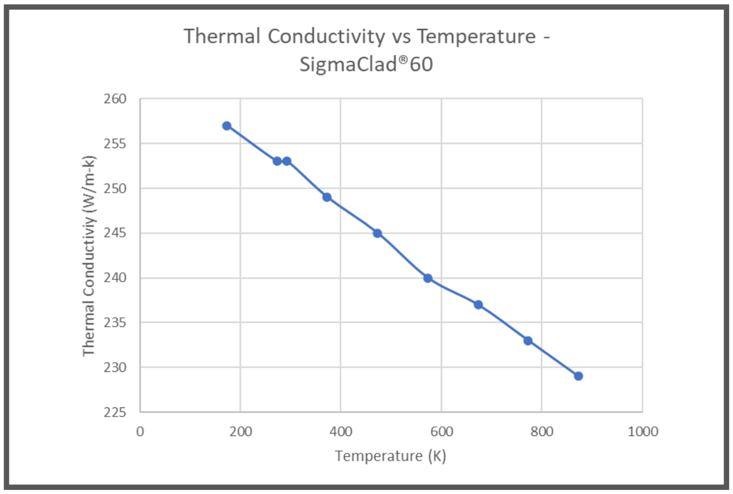

Formability: Erichsen Cup Heights for Battery Tab Materials
Erichsen Cup Height (mm)
0
2
4
6
8
10
12
14
SIGMACLAD (Annealed)
Copper Alloys
Nickels
SIGMACLAD-60
SIGMACLAD-40
N02201 (1/4 Hard)
899A (1/4 Hard)
C7035-TM06

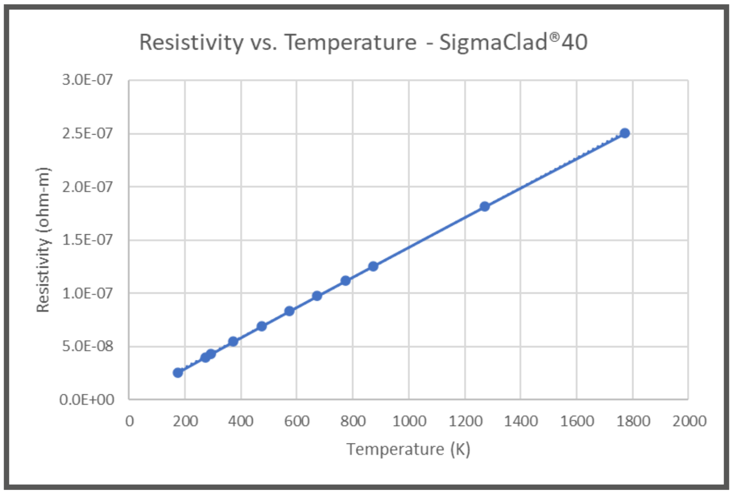

Tensile Strength for Battery Tab Materials
Tensile Strength (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
SIGMACLAD
Copper Alloys
Nickels
Ni Plated Steel
C64770-H03
SIGMACLAD-40
C50710-H02
N02201 (1/4 Hard)
899A (1/4 Hard)
Ni Plated Steel (annealed)
SIGMACLAD-60

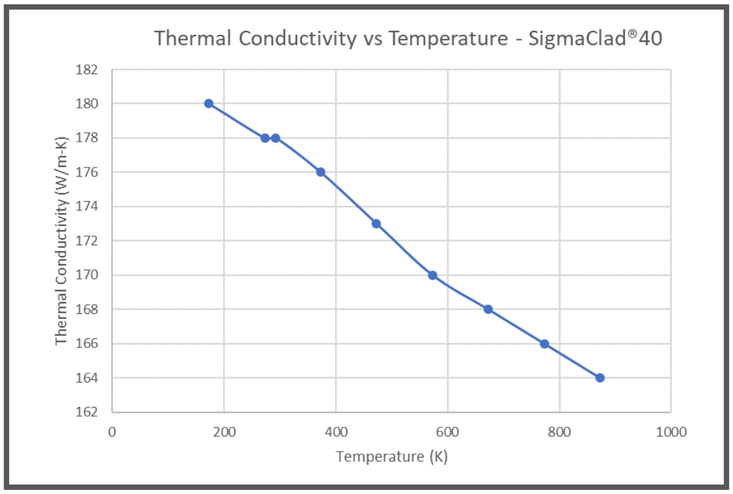
SIGMACLAD® Properties Over Temperature

Properties over temperature are given for Thermal Conductivity and Electrical Resistivity in the graphs below (these are needed for accurate CFD analysis / Thermal modeling).



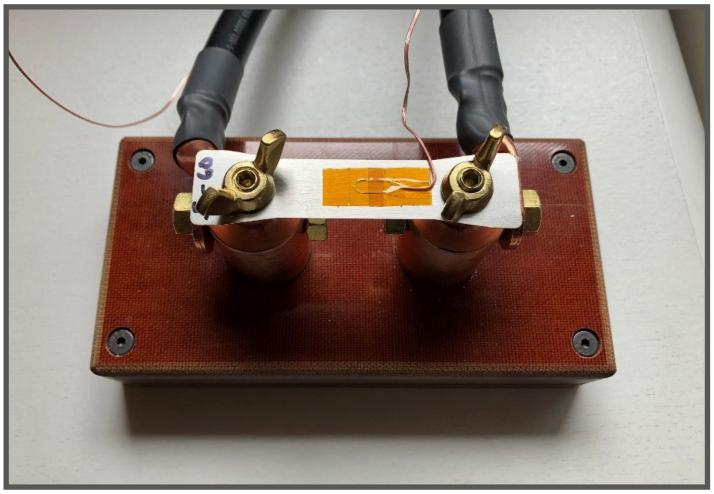


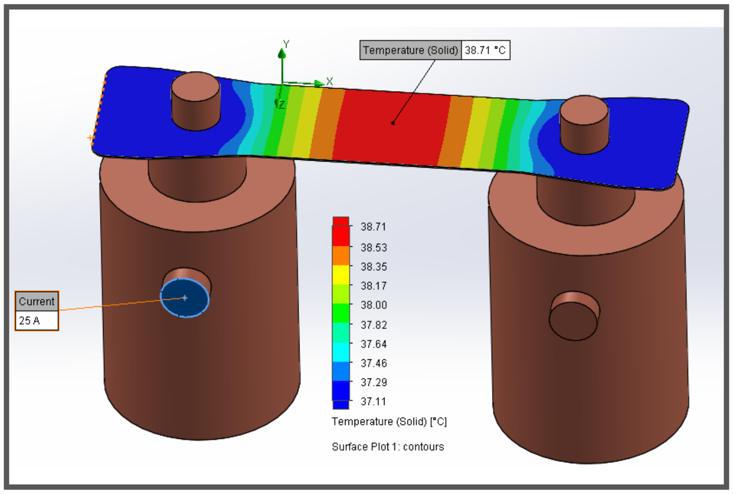




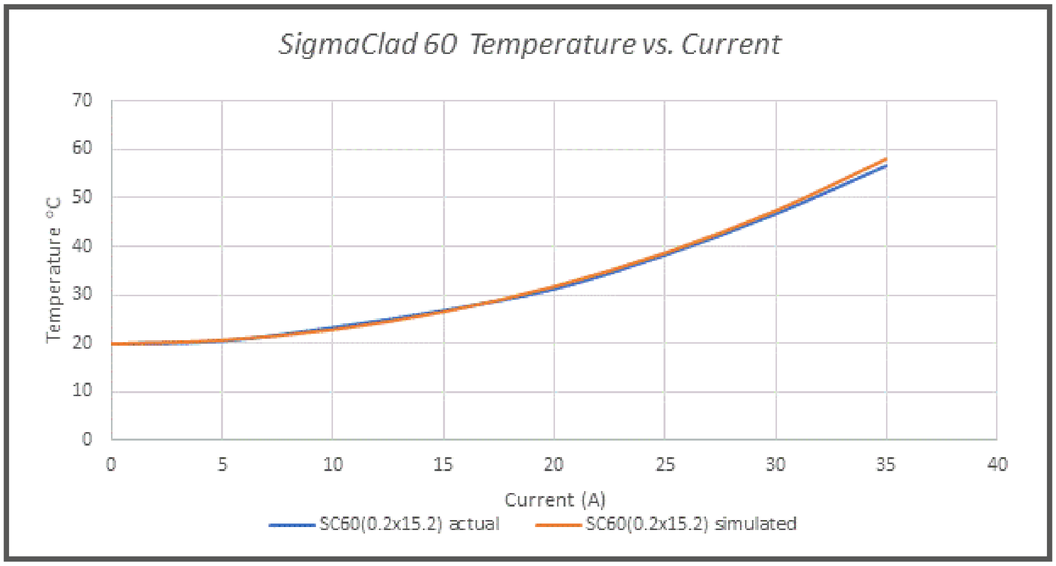
Ampacity Data

Ampacity is defined as the maximum amount of current that a conductor can carry continuously under the conditions of use without exceeding its temperature rating. Several cross-sectional areas of SIGMACLAD® material have been measured and are presented in graphical format. These graphs can help the battery pack designer determine the proper material given the applications current range. The actual test fixture, test data, and thermal model results for SIGMACLAD® 60 (0.20 X 15.2) mm^2 materials are shown below.



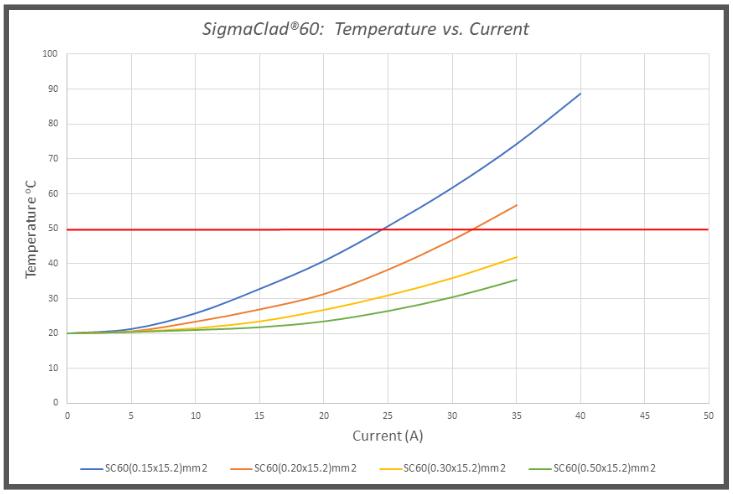


GRAPHICAL RESULTS (ACTUAL AND SIMULATED)

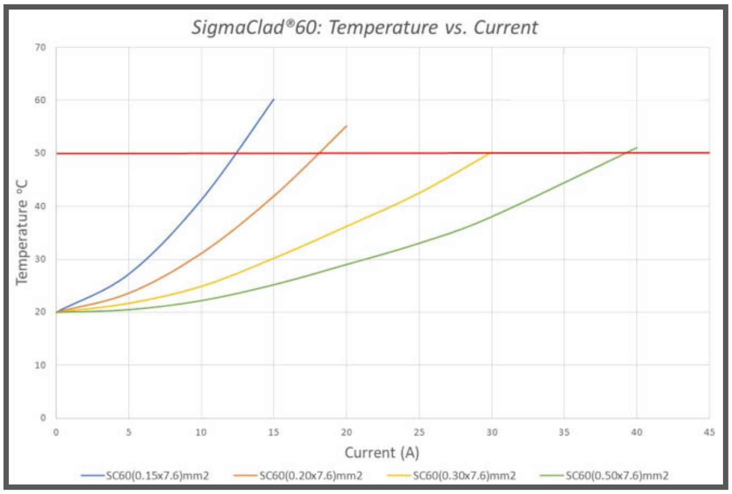


Ampacity Data Graphs

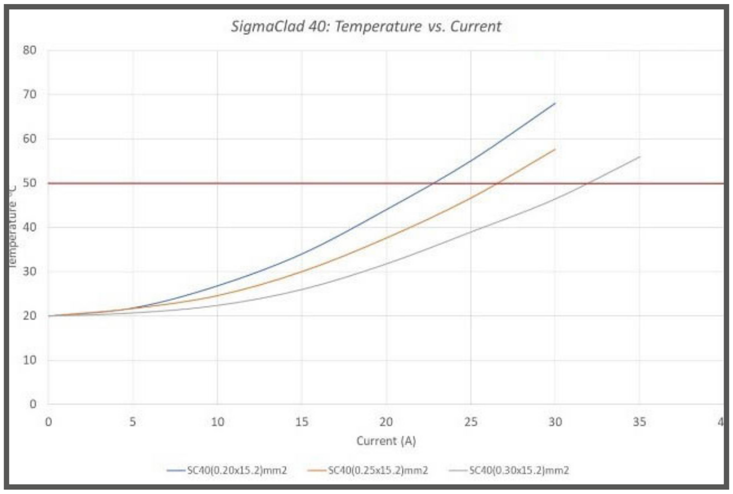
SIGMACLAD® 60 (15.2 mm wide test coupon)



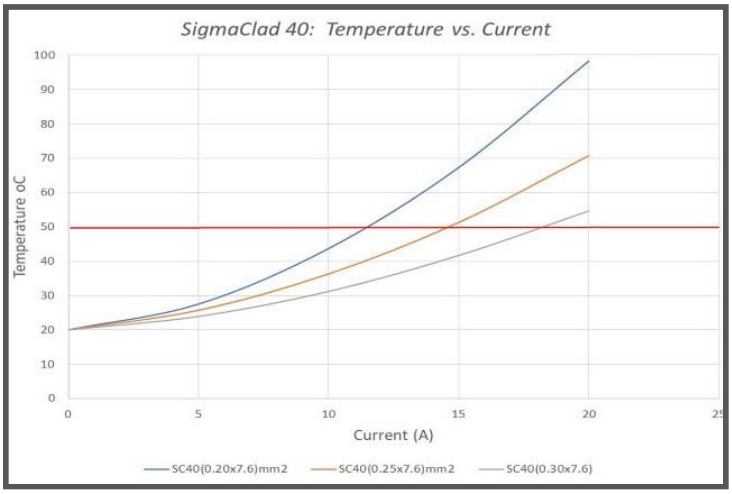
SIGMACLAD® 60 (7.6 mm wide test coupon)

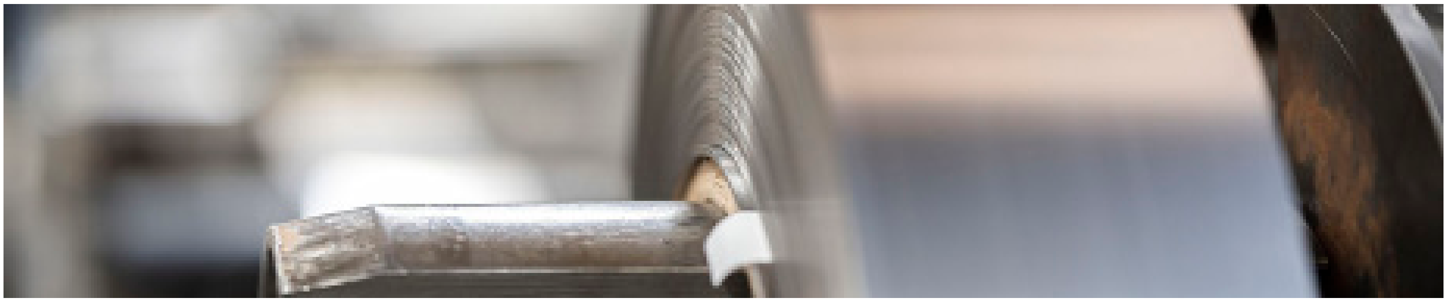


SIGMACLAD® 40 (15.2 mm wide test coupon)

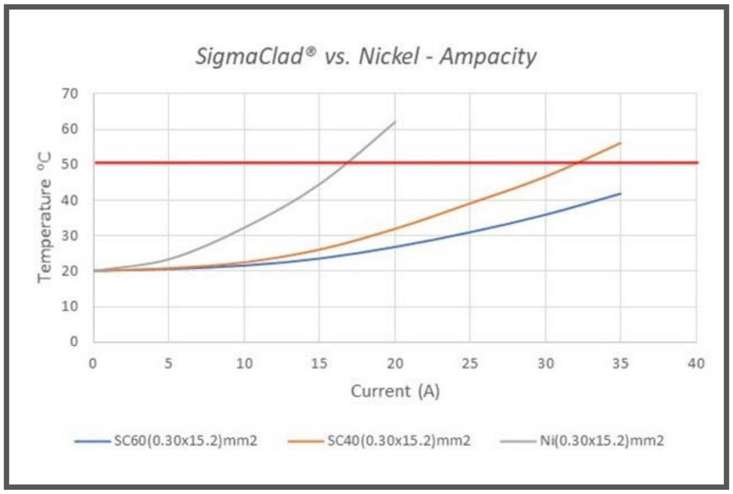


SIGMACLAD® 40 (7.6 mm wide test coupon)

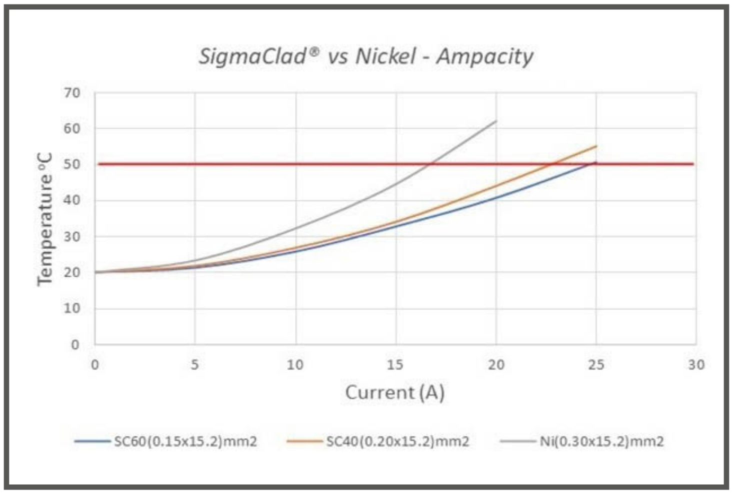




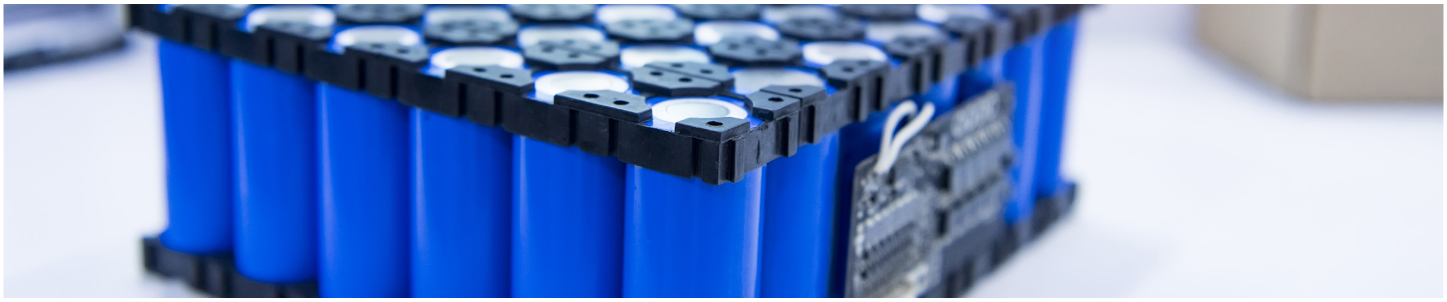
SIGMACLAD® Ampacity is also compared to Nickel to show both performance and cost advantages



Improved performance



Reduced thickness and cost



Ampacity Formula

If the ampacity cannot be determined by the graphs provided, a current density calculation can be used as an initial estimate.

The formula for Ampacity in terms of current density is as follows

$I_{MAX} = J \times A$

I_{MAX} = the maximum current limit not to exceed 50^{0C} in amperes
J = current density in amperes/mm2
A = cross sectional area in mm2

Current Density (table 1)	
Material	**Average Current Density - J (A/mm^2)**
SIGMACLAD®60	*10.5
SIGMACLAD®40	*7.5
NICKEL (201)	*3.8

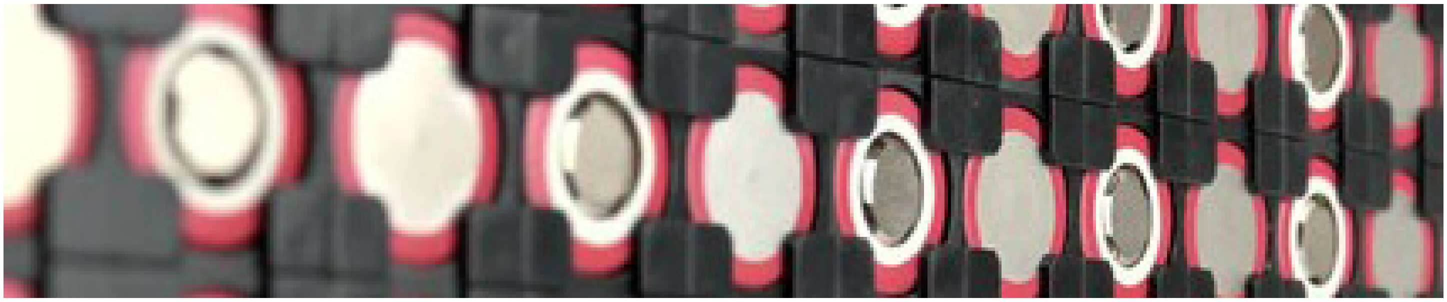
Example:

Determine the maximum current for both Nickel and SIGMACLAD® 60 that have a cross section of 0.20 mm x 10.0 mm.

Nickel: I_{MAX} = 3.8 A/mm2 x (0.20 mm x 10.0 mm) = 7.5 amperes

SIGMACLAD® 60: I_{MAX} = 10.5 A/mm2 x (0.20 mm x 10.0 mm) = 21 amperes

*Note: Current Density parameter assumptions
1. Ampacity target temperature is 50^0C
2. Shape of test coupons: Flat strip 7.6 mm & 15.2 mm in width at various thicknesses (0.1 – 0.5)
   a. Sizes outside these ranges may result in additional error.
3. Environmental conditions: 20^0 C in still air.



Electrical Resistivity and Resistive Heating

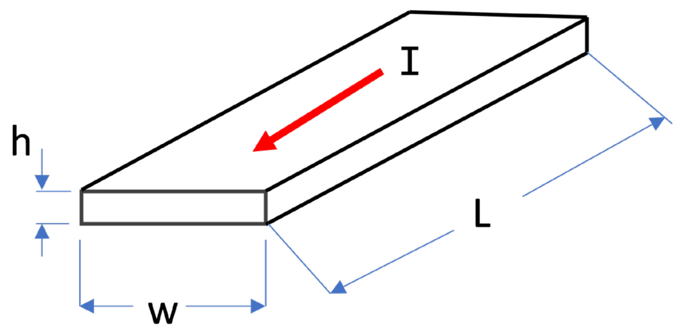
Li-ion battery bus bars, connector tabs, and current collector plates carry large currents resulting in temperature rise caused by Joule Heating. Temperature rise can be calculated for short time durations, when heat loss by conduction, convection, and radiation are negligible, using the following equations.

From Joule's First Law, and electric current has a heating effect of:

EQ1: $Q = I^2 R t$

Where

Q = heat in joules (watt-sec),
R = resistance in ohms,
I = current in amperes,
t = time in seconds



Resistance can be calculated as follows:

EQ2: $R = \rho l/A$

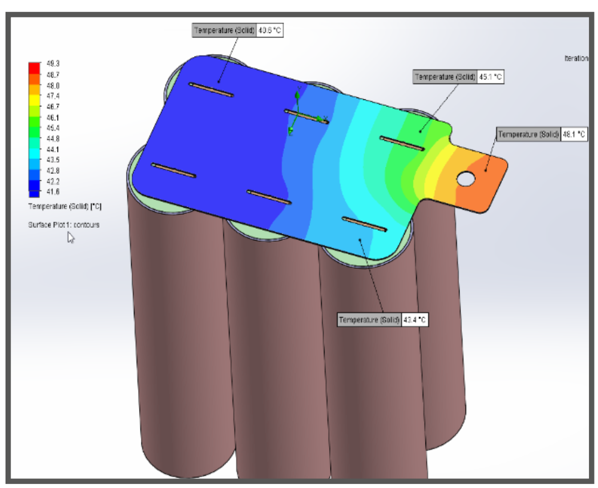
Where
ρ = electrical resistivity in ohm-m
L = length in meters
A = cross sectional area in m^2; width (w) x height (h)

The relationship between Joule heating and temperature rise is given by:

EQ3: $Q = c\, m\, \Delta T$

Where

c = specific heat in J/Kg^{0}C
m = mass in Kg
ΔT = temperature rise in ^{0}C



The mass can be calculated by knowing the materials volume and density as shown:

EQ4: $m = D\ (h \times w \times L)$

Where

D	=	material density in Kg/m^3
h	=	material thickness in meters
w	=	material width in meters
L	=	material length in meters

By substitution, the formula for temperature rise is as follows:

EQ5:

$$\Delta T = (T_{final} - T_{initial}) = \frac{I^2 \rho t}{D h^2 w^2 c}$$

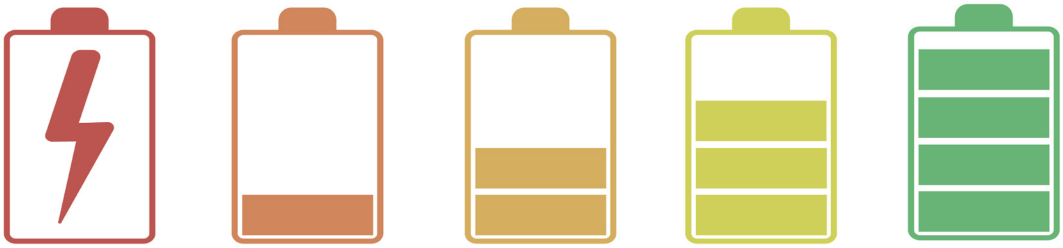
This formula can be useful in determining the maximum allowable current for the battery connection tab, to ensure that the application does not exceed a final temperature of 50^{0}C (recommended maximum temperature for most li-ion battery cells).

This formula does not account for heat loss and can be cumbersome with complicated tab geometries. In these cases, thermal modeling (CFD) and physical testing are recommended to determine the maximum application heat rise.

Example: Determine the final temperature of SIGMACLAD®60 that is 15 mm wide and 0.50 mm thick with 50 amps of current for 20 seconds. Assume a room temperature of 20^{0}C

From EQ5 and the SIGMACLAD®60 material properties in table 1

T_{final} = [({50A}^{2} x 2.87E-8 ohm-m x 20 seconds) / (8580 Kg/m^3 x {0.0005 m}^{2} x {0.015 m}^{2} x 423 J/Kg^0 C)] + 20^{0}C = 27^{0}C



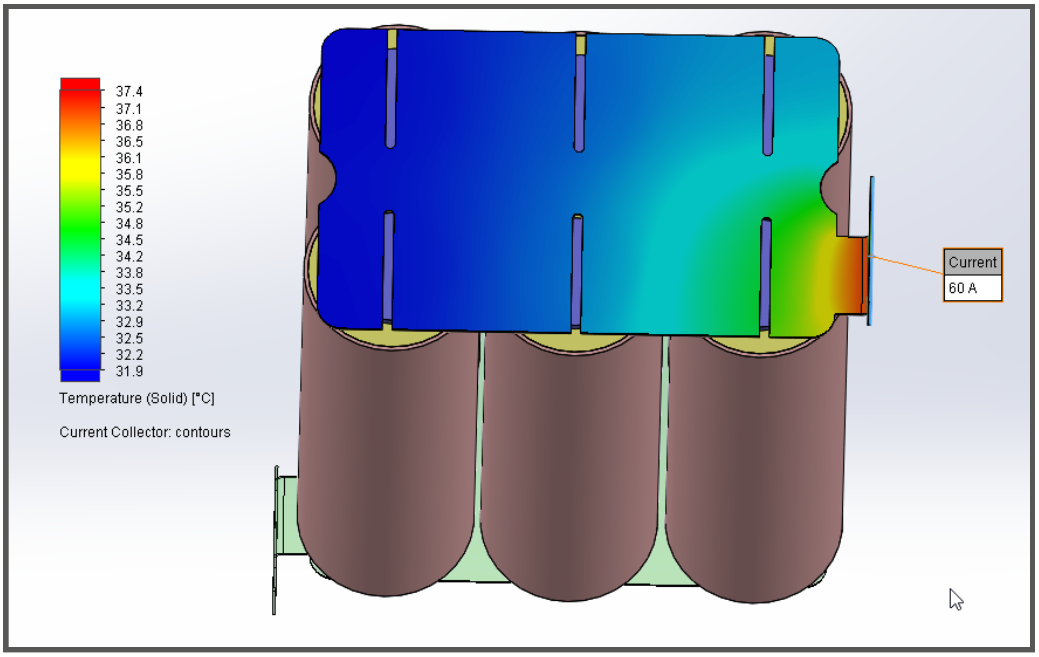
Thermal Modeling

Thermal modeling / Computational Fluid Dynamics (CFD) is recommended for initial design work for new pack connection systems. When just evaluating the connection system (tabs, current collectors, or busbars), a simplified battery cell geometry can be utilized to act as the current source and thermal load.

This methodology allows for fast comparisons of various material system and geometries that can later be validated with actual prototypes. This should reduce the amount of physical testing required.

The illustration below shows a steady state model of a six-cell system (1s6p) with each cell providing 10A (60A exits the current collector as shown). The current collector is made of 0.3mm SIGMACLAD®60 and the environment is still air at 20°C.

You can clearly see the current collector's temperature gradient as well as its maximum temperature.

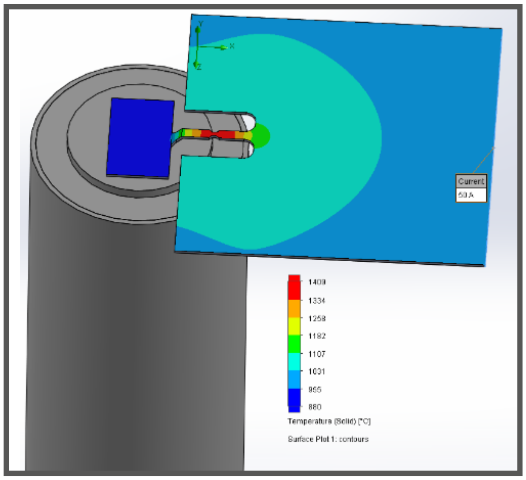


This designer guide provides the various material properties required for CFD analysis.
Electrical resistivity (ρ), and thermal conductivity (k) material properties are temperature dependent and can be found as graphical data in this guide.

Contact EMS directly for questions pertaining to thermal modeling of battery pack connection systems.

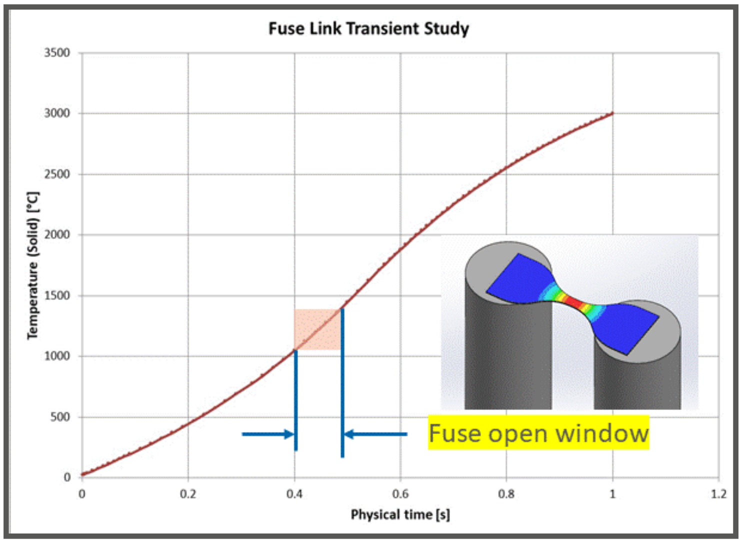
Current collectors, tabs, and busbars can utilize narrow cross sections to act as a fuse in certain high current events (short circuits). Thermal modeling and physical testing are required to ensure the fuse opens under the desired current and time conditions.

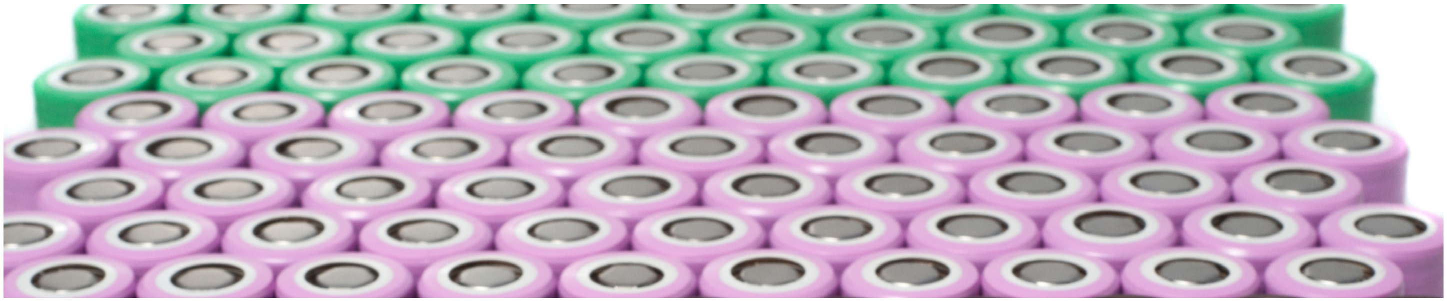
The thermal model shown below is of SIGMACLAD® 40 (0.30 mm x 1.0 mm) and subjected to 50 amperes. The model predicts that the steady state temperature (in still air) is reaching the melting point of the stainless-steel layer and should fuse open under these conditions.



Time dependent model or physical test should be conducted to determine when the fuse will open.

In the example below, a 0.30 mm x 3.0 mm cross section subjected to 300A is reaches the melting point window in approximately 0.4 seconds. The fuse open window should take place between the melting point of copper (1,000^{0}C) and the melting point of 304 stainless steel (1,400^{0}C). The actual time may vary due to the physical design and test conditions.





SIGMACLAD® Cost Savings / Material Gauge Reduction

When converting from nickel to SIGMACLAD®, a gage reduction can be realized while maintaining similar or higher performance (same heat rise).

The following formula can be used as a guide to calculate the new material gage knowing the electrical conductivity of the existing material and of SIGMACLAD®.

% IACS is defined as the electrical resistivity of copper divided by the electrical resistivity of another material. With coppers having a % IACS of 100%

EQ6: $\%IACS = (\rho_{cu} / \rho_1) \times 100$

Where

ρ_{cu} = the electrical resistivity of copper which is 1.7241×10^{-8} ohm-meters
ρ_1 = the electrical resistivity of material 1

In comparing two material systems, set the resistances to be equivalent, and substitute resistivity in terms of %IACS to obtain a relationship between %IACS and thickness (h).

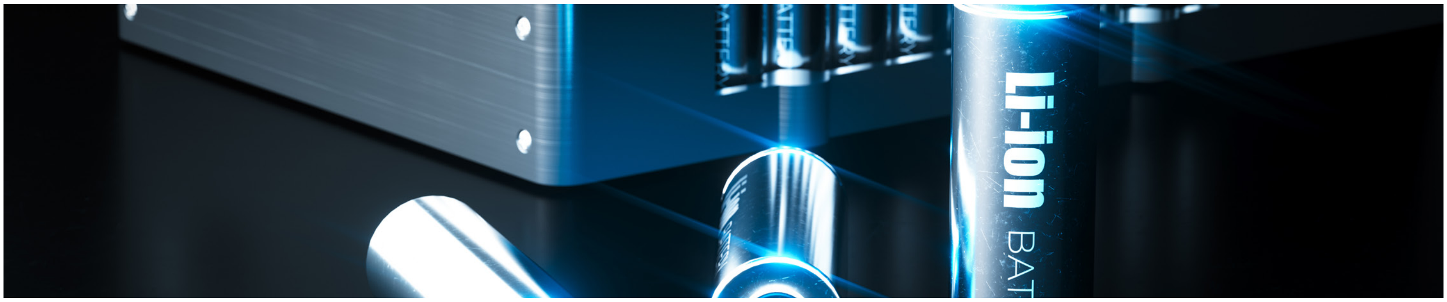
$R_1 = R_2$: which is the same as: $\rho_1 L_1 / h_1 w_1 = \rho_2 L_2 / h_2 w_2$
But $w_1 = w_2$ and $L_1 = L_2$ when only changing the material thickness in the application

Therefore $\rho_1/h_1 = \rho_2/h_2$
With $\rho_1 = \rho_{cu} / \%IACS_1$ and $\rho_2 = \rho_{cu} / \%IACS_2$

By substitution $h_2 = (\%IACS_1 \times h_1) / \%IACS_2$

Example: Determine the equivalent material gage of 0.3mm nickel strip using SIGMACLAD 60 where the %IACS of Nickel is 20% and the %IACS of SigmaCLAD 60 is 60%.

The new gage (h_2) = (20% x 0.30mm) / 60% = 0.1 mm



Corrosion Resistance

SIGMACLAD® was also characterized for corrosion resistance and compared to competing materials.

The corrosion testing was exposure to a corrosive dip in ASTM 2570 water, followed by 16 hours exposure in a condensing humidity chamber (100% RH, 37.70C). Sixty cycles of testing were completed.

SIGMACLAD® materials displayed excellent corrosion resistance, similar to that of nickel strip, after 60 cycles of the corrosive dip test. Conversely, the copper alloys showed severe corrosion, which could lead to reliability issues in service for humid environments.

NI 2201

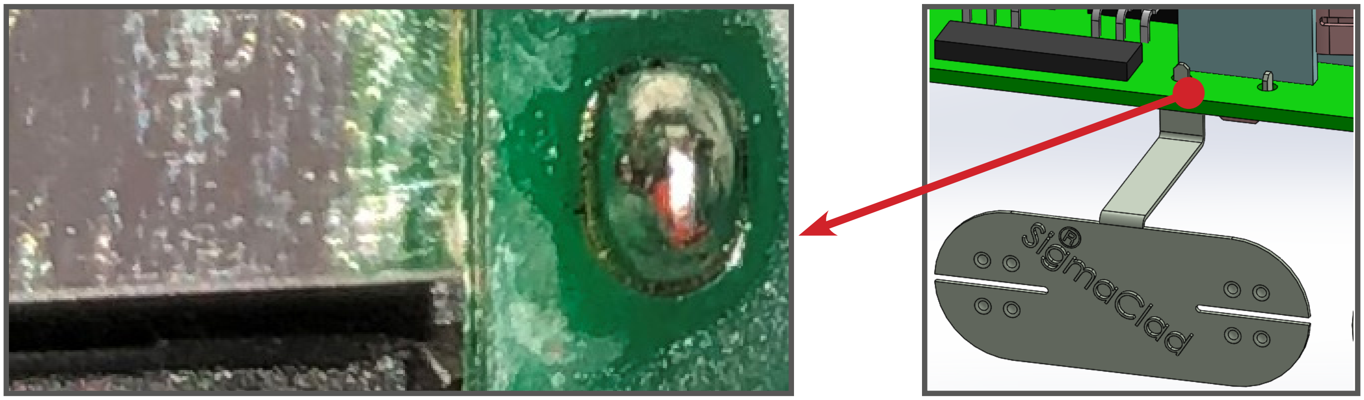
SIGMACLAD®

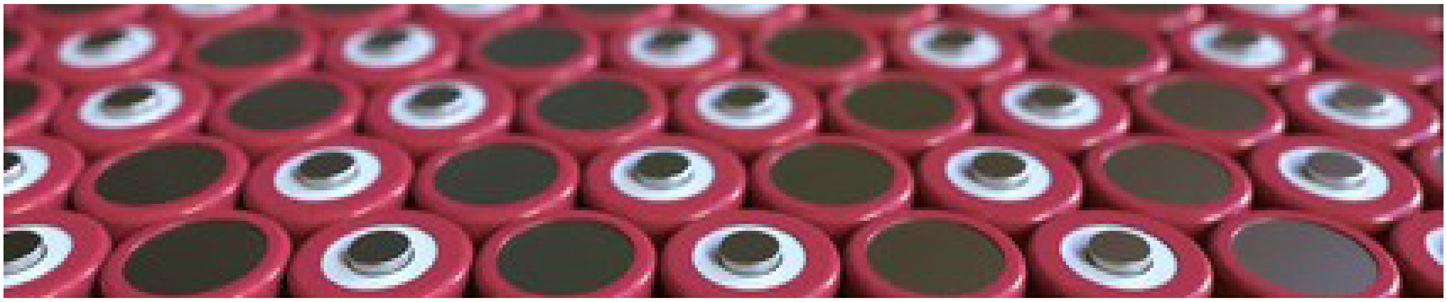
C7035-TM06

Sn-Plate
C19025

Solderability

The exterior layers of Nickel allow for easy soldering. The cold rolling process facilitates an easy soldering process which does not require pre-soldering steps. The process provides good surface wetting and material compatibility that allows direct soldering to PCB.





Resistance Welding

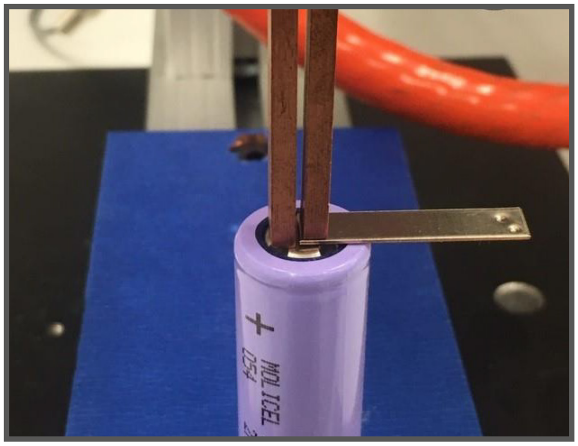
SIGMACLAD® was specifically designed with the welding process for assembling battery packs in mind. The material can be resistance welded, laser welded, ultra-sonically welded and wire bonded.

SIGMACLAD® resistance welds readily using either Parallel or Step Welding processes. The Stainless-Steel layer facilitates strong resistance weld providing excellent weld strength. Excellent pull strengths are observed for multiple conductivity levels and strip thicknesses.

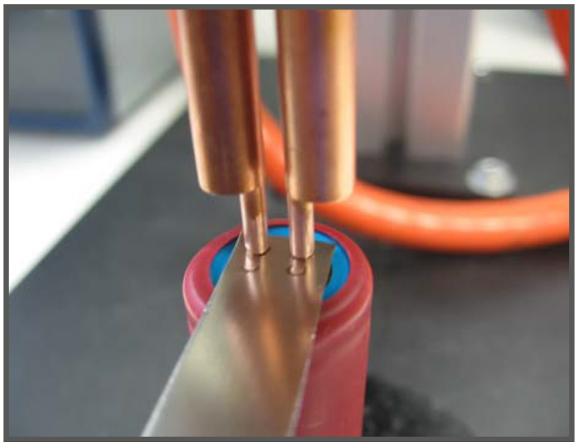
Due to the conductivity of the material, anti-shunt slots and welding projections are recommended for the resistance welding process. EMS can assist in the parameters and design of the welding projections.

Engineered Materials Solutions has worked very closely with AMADA Miyachi and has extensive case studies on the welding process of SIGMACLAD®. EMS can provide the case studies upon request. Please see the welding parameters for the SIGMACLAD® material below:

Material & Thickness	Electrode Config.	Anti-Shunt Slots? / Projections?	Weld Energy	Pull Strength (Kgs) Cathode/ Anode
SIGMACLAD® 40 0.250 mm	parallel	Yes/Yes	150	23/28
SIGMACLAD® 40 0.400 mm	parallel	Yes/Yes	250	30/20
SIGMACLAD® 60 0.381 mm	parallel	Yes/Yes	275	23/31
SIGMACLAD® 60 0.508 mm	parallel	Yes/Yes	500	48/35
SIGMACLAD® 60 0.508 mm	step	No/Yes	150	38/38

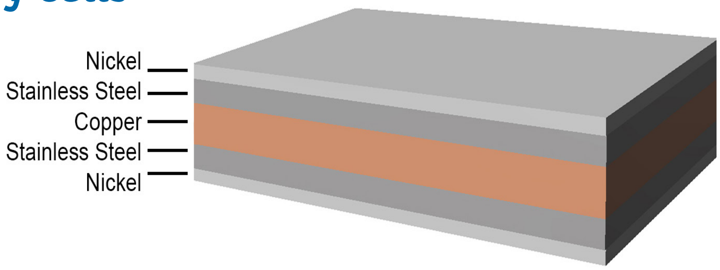


Step Weld



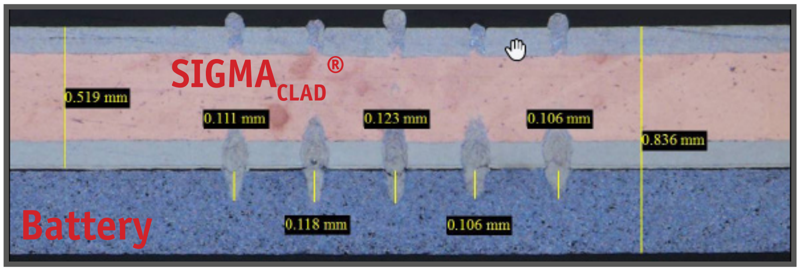
Parallel Weld

Laser Welding SIGMACLAD to Battery Cells



SIGMACLAD® has been successfully laser welded to battery cells using the appropriate laser equipment and settings. In addition, the cell connectors can be laser welded to the top of the cell (anode and cathode) for enhanced pack manufacturability and cost (left side picture).

21700 Cell Laser Welded



Laser Welded Cross Section

- Laser Welder: Fiber optic high beam quality laser.
- Cell Connector: 0.50 mm SIGMACLAD®60
- Weld penetration average 0.113 mm; no damage to cell can (1/3 penetration allowed).
- Mechanical Strength: A spot weld with 5 lines had an average tensile of 120 N.
- Electrical Resistance of spot weld: approximately 130 micro-ohms.
- Weld process can be further optimized based on requirements for electrical resistance, weld strength, and weld penetration.

Parts Manufacturing

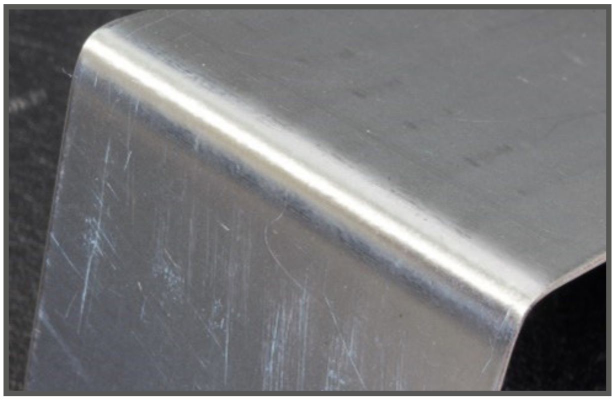
Parts can be fabricated from SIGMACLAD® material in a variety of manufacturing methods; typically, conventional progressive stamping is used for high volume production while laser cutting, and secondary forming are used for low volumes and prototypes.

SIGMACLAD® forms and cuts very similar to austenitic stainless steel in the fully annealed condition. No special tooling and cutting materials are required.

After parts are manufactured, they are cleaned using an ultrasonic aqueous cleaning process and then air dried. SIGMACLAD® has excellent formability characteristics and can be drawn to form a cup shape features and weld projections to enhance cell assembly. SIGMACLAD® can also be bent as much as 180 degrees to form tabs and other features required for pack assembly and electrical connections.

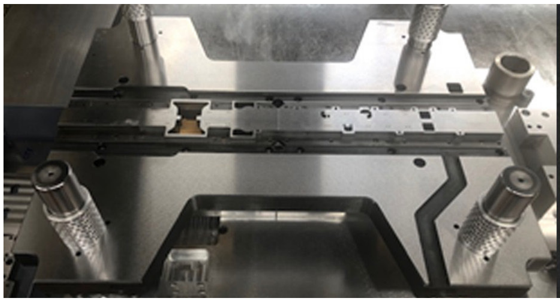
SIGMACLAD® in the annealed condition, can be bent perpendicular and parallel to the rolling direction using a radius of 1x the material thickness without any material fracture. SIGMACLAD® can also be formed in the cold worked condition without cracking using the appropriate bend radius.

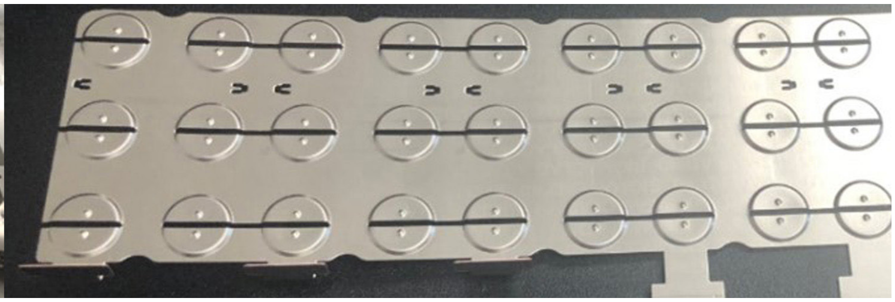
SIGMACLAD® Bending Studies Examples



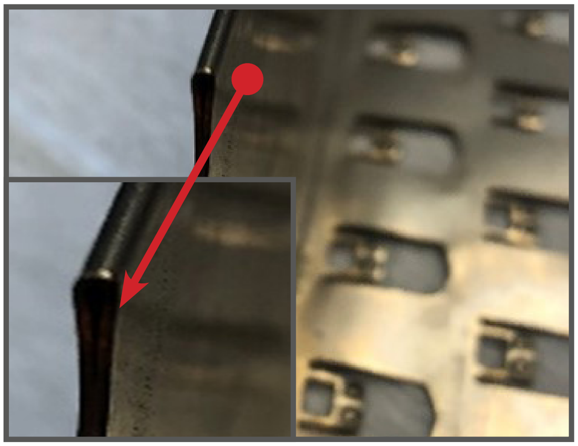
0.50 mm SIGMACLAD®60 annealed, bent 90° parallel to rolling direction (no cracking detected).

0.30 mm SIGMACLAD®40 with 35% cold work bent 90° perpendicular to rolling direction (no cracking detected).

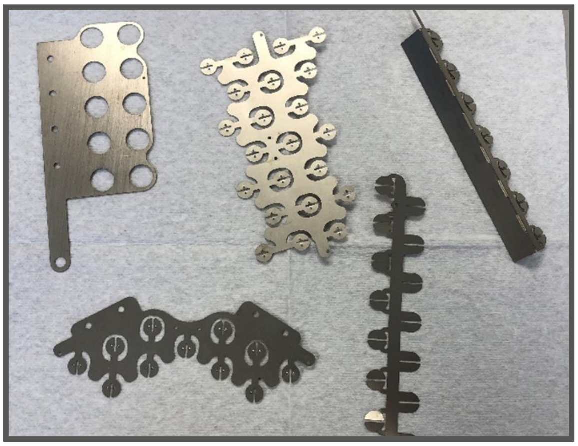




SIGMACLAD® Erichsen Cup height Test Sample



SIGMACLAD® Cell Connector with 180° bend



SIGMACLAD® Cell Connector Component Stamping, Laser Cutting, and Secondary Forming Examples

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