U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Advanced Manufacturing Gap Analysis and Comments on Design and Manufacturing

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August 11, 2022

conceptual design • components • integration • mass production • heliostat field

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Outline

- Advanced Manufacturing topic area gap analysis
- Observations on High-Performance Manufacturing
- Wagon Wills presentation

Advanced Manufacturing Gap Analysis

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
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Topic: Advanced Manufacturing

Roadmap Study – Advanced Manufacturing Study Method (Co-Lead: Parthiv Kurup)

Inputs:

- Estimating value of autonomy survey (prior work).
- HelioCon Roadmap Workshop, Advanced Manufacturing breakout sessions.
- Interviews with industry experts. Companies contacted include:
  - BrightSource Energy
  - COBRA
  - Gonzalez Group
  - Heliogen
  - SkyFuel (retired)
  - Solar Dynamics
  - Solar Reserve (retired)
  - Tewer
  - University of Arizona

Topic: Advanced Manufacturing

Roadmap Study –

Initial List of Gaps

No.	Gaps
Knowledge for product design	
AM1	Lack of a stable market enabling continuous improvement
AM2	Wind load data/analysis to enable mass reduction
AM3	Optimum heliostat utilizing composite facet/array designs not fully understood
AM4	Lack of experience designing heliostats for high-productivity manufacturing: o Access to expertise in early design phases (e.g., high-volume, automotive) o Developers don't know how to find automation providers
AM5	Trade-off between face-up and face-down stow not fully understood
AM6	Variable focus heliostats and their economic benefit not understood
AM7	Rules of thumb for fabrication, material, and component costs
AM8	CAD-based tolerance analysis for mirror array backing structures
Knowledge for process design	
AM9	Facet/array fabrication process knowledge, with multiple prescriptions: o Injection molding o Wide-area adhesive application o Sandwich construction o Frame attachment o Canting control o Knowledge and use of fastening technologies o Material alloy and thickness selection for efficient manufacture
AM10	Lack of experience designing high-productivity manufacturing lines: o Access to expertise in early design phases (e.g., high-volume, automotive) o Developers don't know how to find automation providers o Risks from lack of automation experience o Perception of required capital not sufficient
AM11	Field installation automation support
Standard designs	
AM12	Standard facet specification
AM13	Standard facet production, including multiple prescriptions
AM14	Standard baseline design
Metrology and calibration	
AM15	Specialized metrology tools not mature enough for factory use o Not compatible with factory environment o Calibration checks o Statistical process control
AM16	Metrology for molds
AM17	Metrology for mirror array backing structures

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<u>**Selected industry comments (paraphrased):**</u>

There are two fundamental design approaches to heliostat design which we have seen succeed. In one approach, facets are designed as self-supporting structures that are responsible for achieving optical tolerances as a stand-alone unit. These are then assembled into an array, and canting angles set to achieve overall heliostat optical shape. In the second approach, individual mirror facets are not self-supporting, and do not achieve their final optical shape until included in a mirror array which simultaneously determines the facet optical shape and overall heliostat canting and optical shape. Among these, the second method can achieve the lowest cost, but it requires very rigorous execution of the final assembly step.

Our future vision of heliostats is facet mirrors that are composite structures, with 1.1 mm commercial glass mirrors supported by a rigid backing structure. This has several advantages: Reduced material cost, weight and reduced structural support, all of which reduce cost, increased reflectivity (from 94% to 96%), increased stiffness, and increased operation in wind, all of which increase energy production, plus additional cost reduction due to decreasing the solar field size by 2%.

Engaging automation developers early in the heliostat design process is important achieve high automation performance.

Some heliostat developers do not have experience designing with material alloys and thicknesses that are customized for high-volume manufacturing. This is common practice in the automotive industry. Automotive Advanced High Strength Steels (AHSS) can offer significantly higher strength but retain good weldability and formability. Automotive steel grades that come in coil form are also typically readily available with galvanized coatings. Automotive aluminum grades are available with pretreatments for adhesive bonding so surface prep, which is critical in adhesive bonding of aluminum, isn't necessary.

Ranked Gaps

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From the Roadmap:

Tier 1 Gaps (Most Important)	
AM1	Innovative heliostat mirror facet/array designs needed ○ Example: composite designs
AM2	Insufficient facet/array fabrication process knowledge, including: ○ Injection molding ○ Wide-area adhesive application ○ Laminated mirrors ○ Sandwich construction ○ Frame attachment ○ Canting control ○ Knowledge and use of fastening technologies ○ Material alloy and thickness selection for efficient manufacture ○ Composite structures
AM3	Heliostats not designed for high-productivity manufacturing, due to: ○ Lack of access to expertise in early design phases (for example, high-volume, automotive) ○ Developers don't know how to find automation providers
AM4	Lack of heliostat developers' experience designing high-productivity manufacturing lines, due to: ○ Lack of access to expertise in early design phases ○ Difficulty finding automation providers ○ Risks from lack of automation experience ○ Perception of required capital is not sufficient
Tier 2 Gaps	
AM5	Trade-off between face-up and face-down stow not fully understood[1]
AM6	Variable focus heliostats and their economic benefit not understood
AM7	Lack of field installation and quality assurance automation support
AM8	Specialized metrology tools not mature enough for factory use ○ Not compatible with factory environment ○ Calibration checks ○ Statistical process control
AM9	Lack of knowledge about creep behavior of adhesives and PU foams (used for sandwich constructions)
AM10	Lack of knowledge of typical ground conditions for foundation design
AM11	Lack of low-cost production method for concrete foundation elements
AM12	Lack of a standard baseline design
Tier 3 Gaps (Least Important)	
AM13	Lack of rules of thumb for fabrication, material, and component costs
AM14	No CAD-based tolerance analysis for mirror array backing structures
AM15	Lack of a standard facet specification
AM16	No standard facet production methods, including multiple prescriptions
AM17	Metrology for molds not widely understood
AM18	Metrology for mirror array backing structures not widely understood

[1] Reviewer pointer: Blackmon, J. B, "Non-Inverting Heliostat Study", Sandia Report SAND78-8190, July 1979.
https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/1978/788190.pdf

Observations on High-Performance Manufacturing

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High-Performance Manufacturing Notes*

The most important takeaway:

- Many companies design a product, and then consider manufacturing. This is a lost opportunity.

  The highest-performance manufacturing results from considering high-productivity manufacturing from the start of design.

- High-performance manufacturing vendors actively support this.
  Nonetheless, they still encounter customers who engage them after design.

Key principles:

- Take work out of the design.
- Take parts out of the design.
- Take material out of the design.
- Seek solutions which simultaneously increase quality and reduce work.
- Select processes which inherently produce high quality at high speed.
- Select materials which enable these processes.
- Invent to fill gaps if needed.
- Select tooling for high productivity, considering production volume and target takt time.
- Ensure high quality control at many steps along the process – don't add value to defective work.
- Employ automation for the benefits it brings to each specific design, not "for automation's sake."

* Drawn from Randy Brost's experience – GM collaboration, Kodak, SkyFuel.

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High-Performance Manufacturing Notes

Examples:

- Screws vs. snap-fit.
  - *Screws:* Multiple parts, multiple handling operations $\Rightarrow$ speed limited.
  - *Snap-fit:* Single pick-and-place operation. Caveat: Screws are removable!
- "What's good for the robot, is also good for the human." – Professor Dan Whitney, MIT.
- IBM Pro Printer design for assembly (https://www.youtube.com/watch?v=spDYSKl3kmo).
- Consumer products – synchronous vs. flexible assembly (https://arthurgrussell.com/, https://flexomation.com/).
- Surface mount electronic components (http://www.surfacemountprocess.com/).

Assembly

- Injection mold hardness and cavity number selection (https://www.protolabs.com , https://www.fastradius.com/resources/single-cavity-vs-multi-cavity-injection-molding/, https://www.xcentricmold.com/).
- Roll-based manufacturing (https://www.superiorrollforming.com/)
- Precision machine design, fixturing, machine vision (https://www.americanmachinist.com/archive/features/article/21896912/the-many-parts-of-high-precision, https://www.xometry.com/capabilities/cnc-machining-service/, https://www.cognex.com/).
- Semiconductor manufacturing (Suppliers: Clean rooms, vacuum chambers, robots, process equipment, photolithography. Process control and high quality/yield are paramount. Speed is achieved through parallel production).

Fabrication

Topic: Advanced Manufacturing

Selected industry comments (paraphrased):

There are two fundamental design approaches to heliostat design which we have seen succeed. In one approach, facets are designed as self-supporting structures that are responsible for achieving optical tolerances as a stand-alone unit. These are then assembled into an array, and canting angles set to achieve overall heliostat optical shape. In the second approach, individual mirror facets are not self-supporting, and do not achieve their final optical shape until included in a mirror array which simultaneously determines the facet optical shape and overall heliostat canting and optical shape. Among these, the second method can achieve the lowest cost, but it requires very rigorous execution of the final assembly step.

Remove parts and work

Our future vision of heliostats is facet mirrors that are composite structures, with 1.1 mm commercial glass mirrors supported by a rigid backing structure. This has several advantages: Reduced material cost, weight and reduced structural support, all of which reduce cost, increased reflectivity (from 94% to 96%), increased stiffness, and increased operation in wind, all of which increase energy production, plus additional cost reduction due to decreasing the solar field size by 2%.

Increase quality and performance

Engaging automation developers early in the heliostat design process is important achieve high automation performance.

Concurrent product and process design

High-speed, high-quality processes

Some heliostat developers do not have experience designing with material alloys and thicknesses that are customized for high-volume manufacturing. This is common practice in the automotive industry. Automotive Advanced High Strength Steels (AHSS) can offer significantly higher strength but retain good weldability and formability. Automotive steel grades that come in coil form are also typically readily available with galvanized coatings. Automotive aluminum grades are available with pretreatments for adhesive bonding so surface prep, which is critical in adhesive bonding of aluminum, isn't necessary.

Remove work

Wagon Wills Presentation

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Wagon Wills Presentation

Wagon Wills is Chief Engineer at Gonzalez Production Systems and has worked in various engineering roles over the last 16 years. He has worked in product development and on automation projects in numerous industries including automotive, renewable energy, aerospace, and heavy industry. His key areas of interest and expertise are in design for manufacturing, material selection, design optimization, joining technologies, and robotic systems.

Wagon Wills
Chief Engineer, Gonzalez Group
wwills@gonzalez-group.com

Presentation:

"Advanced Manufacturing for Heliostats: What We Can Learn from Automotive Joining Technologies, Materials, and Automation"

Advanced Manufacturing For Heliostats: What We Can Learn From Automotive Joining Technologies, Materials, and Automation

August 11, 2022

Gonzalez Introduction

- Since 1975, the Gonzalez companies are proudly minority and family owned, providing unmatched expertise with the highest quality solutions and services to meet their diverse challenges.
- Gonzalez Group has grown into the automation industry's leading minority-owned enterprise, offering a comprehensive range of engineering, manufacturing, automation integration supporting the Automotive, Heavy Industry, Aerospace and Defense Projects
- Gonzalez strives to be a leading provider of innovative products and services that exceed our customers expectations. Our talented team takes pride in every detail of our services to also include building a positive and sustainable contribution to our communities in which they live and work.

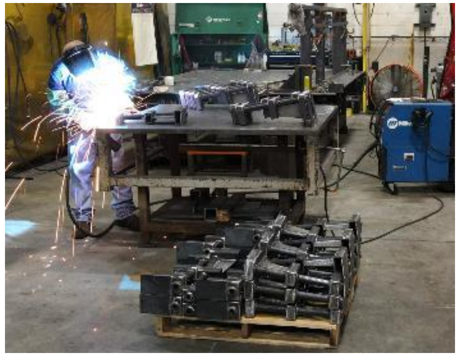
About Gonzalez

Gonzalez is comprised of multiple companies which are positioned to best support our customers with a wide array of services;

- **Production Systems**
  - Turnkey Design, build and integration of automated and manual assembly tools and systems
- **Design Engineering**
  - Mechanical Engineering and design of automated and manual assembly tooling solutions
  - Electrical / Controls Engineering – hardware and software design
  - Contract Process Engineering and Consulting
- **Manufacturing Technologies & Integration**
  - Inhouse fabrication, machine and inspection capacities for tools and automation
  - Complete Process Design and Fabrication of product shipping containers, and racks
- **Contract Services**
  - Permanent and Temporary Staffing Solutions

Company Statistics

- Currently 300 employees
- Certified Small / Minority Business
- +190,000 sq. ft. of Manufacturing Floor Space in the US
- +50,000 sq. ft. of Office Space
- Mechanical Engineering Software;
  - Catia, NX, Fides, Solidworks, Delmia, Process Simulate, ROBCAD, Inventor, Ansys Mechanical, Ansys Discovery, nTopology
- Electrical / Controls Engineering platforms:
  - Allen Bradley, Siemens, and Omron
- Average sales is approximately 50-75M



Heliocon Introduction

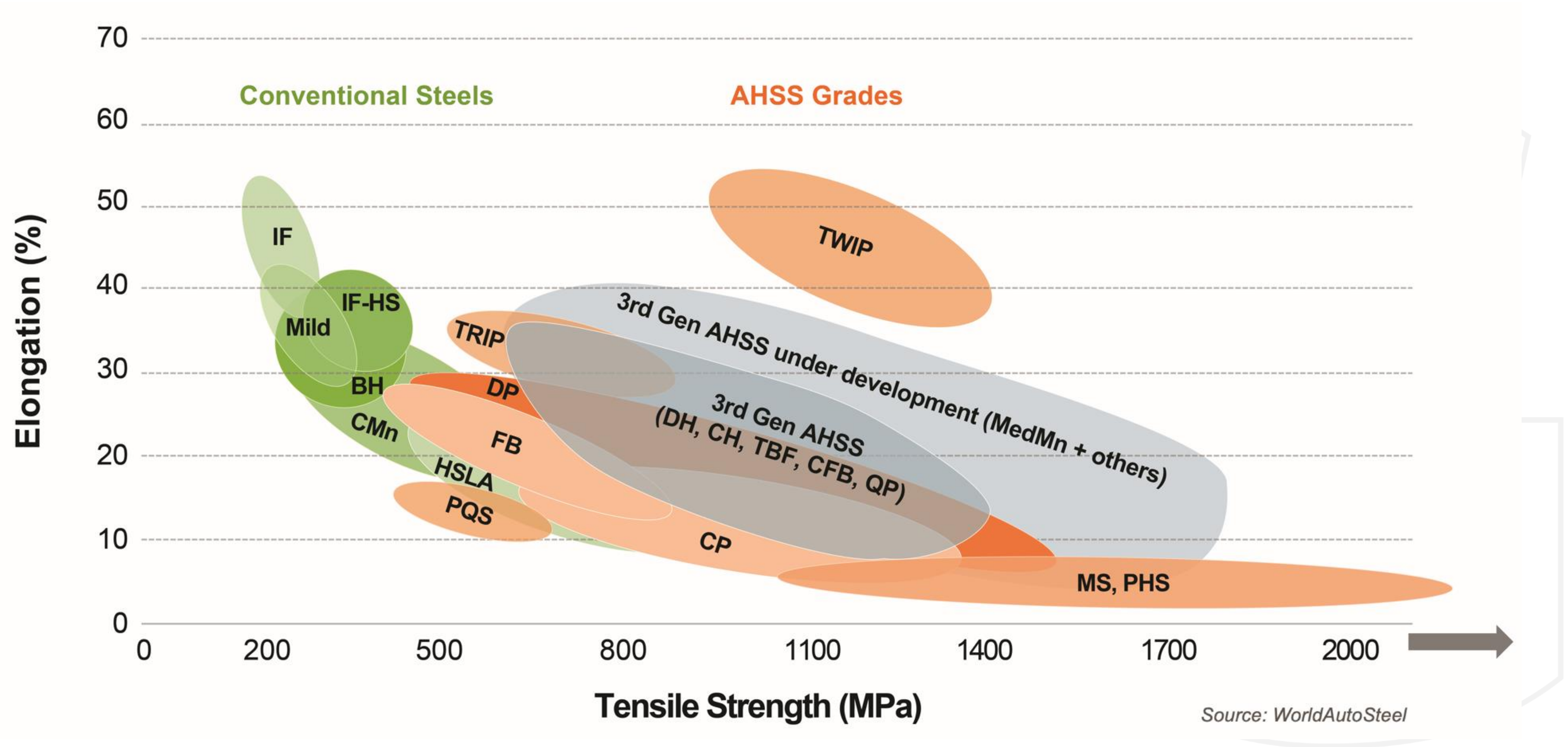
- Gonzalez Production Systems is an automation integrator with extensive experience in the assembly of automotive body structures and closures.
- The problem of manufacturing tens or hundreds of thousands of heliostats and/or facets from thin gauge sheet metal overlaps significantly with our automotive experience.
- Automation offers a path to both cost reduction and increased quality but finding the appropriate balance of automated and manual operations can be difficult.
- There may be efficiencies for CSP OEMs to gain from adopting some automotive body structure manufacturing technologies.
- Simultaneous engineering helps establish a feedback loop between the product design and its manufacturing system to help achieve the best possible cost and performance.

Simultaneous Engineering

- Automation systems can be very significant investments; automotive bodyshops typically cost in the hundreds of millions of dollars. For that cost, the systems provide tremendous productivity and consistent manufacturing.
- To help control the cost of automation systems and reduce project risk OEMs often work with an integrator to concept the automation system to establish cost, floorspace, and equipment requirements. When done during the product development phase, opportunities often arise to make alterations to the design to reduce cost, ease assembly or both within the manufacturing system.
- The scope of the exercise can also include investigations into tradeoffs between joining technologies and material selection in the design.
- Collaboration with an integrator allows the product design team to understand the major driver of costs in the automation system.

Automotive Sheet Materials

Automotive Sheet Steel



Automotive Sheet Steel

Steel Type	Relative Cost	Relative Cost (HDG)
Cold Rolled Mild 140/270	1.00	1.00
BH 210/340	1.07	-
BH 280/400	1.10	-
HSLA 350/450	1.16	1.20
HSLA 420/500	1.19	1.23
HSLA 490/600	1.22	1.25
DP 300/500	1.27	1.30
DP 450/600	1.36	1.38
DP 500/800	1.42	1.44
DP 700/1000	1.52	1.53
DP 1150/1270	1.52	1.53
TRIP 350/600	1.55	1.56
TRIP 400/700	1.62	1.62
TRIP 450/800	1.68	1.68
TRIP 600/980	1.75	1.75
CP 500/800	1.42	1.44
CP 600/900	1.48	1.49
CP 750/900	1.55	1.56
CP 800/1000	1.62	1.62
CP 1000/1200	1.64	1.65
CP 1050/1470	1.64	1.65
MS 950/1200	1.64	1.65
MS 1150/1400	1.66	1.66
MS 1250/1500	1.70	1.70
TWIP 500/980	2.64	2.57

Initials	Type of steel	Initials	Type of steel
IF	Interstitial Free	CFB	Carbide-Free Bainite
IF-HS	Interstitial Free - High Strength	TBF	TRIP-Aided Bainitic Ferrite
CMn	Carbon-Manganese	TR	Transformation Induced Plasticity (TRIP)
BH	Bake Hardenable	QP	Quenching & Partitioning
LA	High Strength, Low Alloy (HSLA)	TW	Twinning-Induced Plasticity (TWIP)
DP	Dual Phase	Med-Mn	Medium-Manganese
DH	Dual Phase – High Ductility	RA	Retained Austenite (encompasses TRIP, QP, TW, med Mn, and others)
CP	Complex Phase	MS	Martensitic
CH	Complex Phase – High Ductility	PQS	Press Quenched Steel
FB	Ferrite Bainite	PHS	Press Hardening Steel

Table 1: Different Types of Steels and Associated Abbreviations.

Strength expressed as kgf/mm²	Strength rounded to nearest 10 MPa	Strength rounded to nearest 50 MPa	Approximate strength in ksi (1,000 psi)	Example grades
45	440	450	65	DP440 - DP450
50	490	500	70	DP490 - DP500
60	590	600	85	DP590 - DP600
70	690	700	100	TRIP690 - TRIP700
80	780	800	115	TRIP780 - TRIP800
100	980	1000	145	DH980 - DH1000
120	1180	1200	170	MS1180 - MS1200
150	1470	1500	215	PHS1470 - PHS1500

Table 2: Syntax Related to AHSS Strength Levels

Source: World Auto Steel - https://www.worldautosteel.org/projects/future-steel-vehicle/phase-2-results/

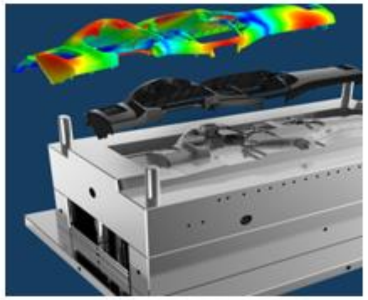
Automotive Sheet Steel

Steel Type	Relative Cost	Relative Cost (HDG)	Yield Strength	Relative Cost Per Unit of Yield Strength	Utimate Tensile Strength	Relative Cost Per Unit of Ultimate Tensile Strength
Cold Rolled Mild 140/270	1.00	1.00	140.00	1.00	270.00	1.00
BH 210/340	1.07	-	210.00	0.71	340.00	0.85
BH 280/400	1.10	-	280.00	0.55	400.00	0.74
HSLA 350/450	1.16	1.20	350.00	0.47	450.00	0.70
HSLA 420/500	1.19	1.23	420.00	0.40	500.00	0.64
HSLA 490/600	1.22	1.25	490.00	0.35	600.00	0.55
DP 300/500	1.27	1.30	300.00	0.59	500.00	0.69
DP 450/600	1.36	1.38	450.00	0.42	600.00	0.61
DP 500/800	1.42	1.44	500.00	0.40	800.00	0.48
DP 700/1000	1.52	1.53	700.00	0.30	1000.00	0.41
DP 1150/1270	1.52	1.53	1150.00	0.19	1270.00	0.32
TRIP 350/600	1.55	1.56	350.00	0.62	600.00	0.70
TRIP 400/700	1.62	1.62	400.00	0.57	700.00	0.62
TRIP 450/800	1.68	1.68	450.00	0.52	800.00	0.57
TRIP 600/980	1.75	1.75	600.00	0.41	980.00	0.48
CP 500/800	1.42	1.44	500.00	0.40	800.00	0.48
CP 600/900	1.48	1.49	600.00	0.35	900.00	0.44
CP 750/900	1.55	1.56	750.00	0.29	900.00	0.46
CP 800/1000	1.62	1.62	800.00	0.28	1000.00	0.44
CP 1000/1200	1.64	1.65	1000.00	0.23	1200.00	0.37
CP 1050/1470	1.64	1.65	1050.00	0.22	1470.00	0.30
MS 950/1200	1.64	1.65	950.00	0.24	1200.00	0.37
MS 1150/1400	1.66	1.66	1150.00	0.20	1400.00	0.32
MS 1250/1500	1.70	1.70	1250.00	0.19	1500.00	0.31
TWIP 500/980	2.64	2.57	500.00	0.74	980.00	0.73

Automotive Sheet Aluminum

- **Consumer Durables-** appliances, cookware, tools, recreational items.
- **Commercial Transportation-** trailers, tankers, cab parts, fuel tanks, steps, door frames, accessories.
- **Automotive Components-** brackets, seat structures, skid plates, gaskets, trim.
- **Building and Construction-** architectural building panels, siding, gutters, spouting, clean room wall panels, sign stock.
- **Electrical-** lighting fixtures, buss bar, dial faces, housings, panel enclosures.
- **Machinery and Equipment-** material handing systems, injection molds, semiconductor chamber parts, tooling and fixturing.







Source: Arconic

Aluminum

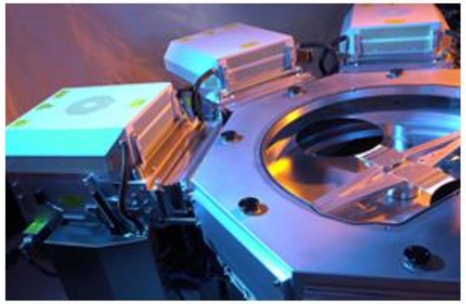
Typical alloys for aluminum products sold into the industrial market

- **1XXX (99% Pure Aluminum)-** 1100, 1050, 1350, 1145.
- **2XXX (Cu additions)-** 2219
- **3XXX (Mn additions)-** 3003, 3105, 3004, 3104.
- **5XXX (Mg additions)-** 5005, 5052, 5754, 5182, 5083, 5082,
- **6XXX(Mg, Si)-** 6061, 6013, 6082, 6111
- **7XXX (Zn)-** 7021, 7075, MIC6


MIC6 Fixture Plate


1XXX Litho Sheet


3XXX Control Panel


6XXX Semiconductor Chamber


2XXX, 7XXX Mold Applications


5XXX Bulk Transport Sheet

Source: Arconic

Aluminum Properties and Applications

Alloy Series	Strength	Ductility	Corrosion Resistance	Product Form	Applications
1xxx (and some 8xxx)	Low	High	Excellent	Sheet, Foil, Wire	Packaging, Electrical, etc.
3xxx	Medium	High	Good	Sheet, Foil	Packaging, Industrial, etc.
5xxx	Medium to high	Medium	Good	Plate, Sheet	Packaging, Commercial transportation, Consumer electronics, etc.
6xxx	Medium to high	Medium	Good	Plate, Sheet, Extrusions, Forgings	Automotive, Building & construction, Mold & tooling, etc.
2xxx & 7xxx	High	Low	Poor	Plate, Sheet, Extrusions, Forgings	Aerospace, Defense, etc.
4xxx	Low melting point			Sheet	Brazing alloys

Source: Arconic

Automotive Sheet Aluminum

- Aluminum sheet in automotive body structures often focuses on the following grades:
  - 5754-O – high formability
  - 5182-O – high formability (higher Mg content limits use in structural applications)
  - 5052-H32 – lower formability, higher strength
  - 6111-T4 – high formability, high strength, heat treatable
  - 6022-T4 – high formability, dent resistance, hemmability, surface finish
- These grades are available at thicknesses ranging from 1mm to 3.5+mm and are available with pretreatments to enhance adhesive performance.
- The 5xxx grades are roughly 20% cheaper and are often the best-cost option for stiffness limited components. The higher strength of the 6xxx grades often makes them the better value in stress limited applications.

Other Automotive Aluminum Alloys

Arconic Automotive Sheet Alloys

	Applications	Products	Key Attribute
OUTERS	 	C4A8 C1A0	Flat hem & sharp styling
INNERS	 	C4A8 C1A0 C6A1 5182 5754	Inner/Deep draw
Structure/ Crash	 	6111 6013 C12Z	High strength/ Energy absorption
HIGH FORM	 	C1A0	High form
HIGH STRENGTH	 	C8A9 New 7xxx C Alloys	Under development

5xxx
6xxx
7xxx

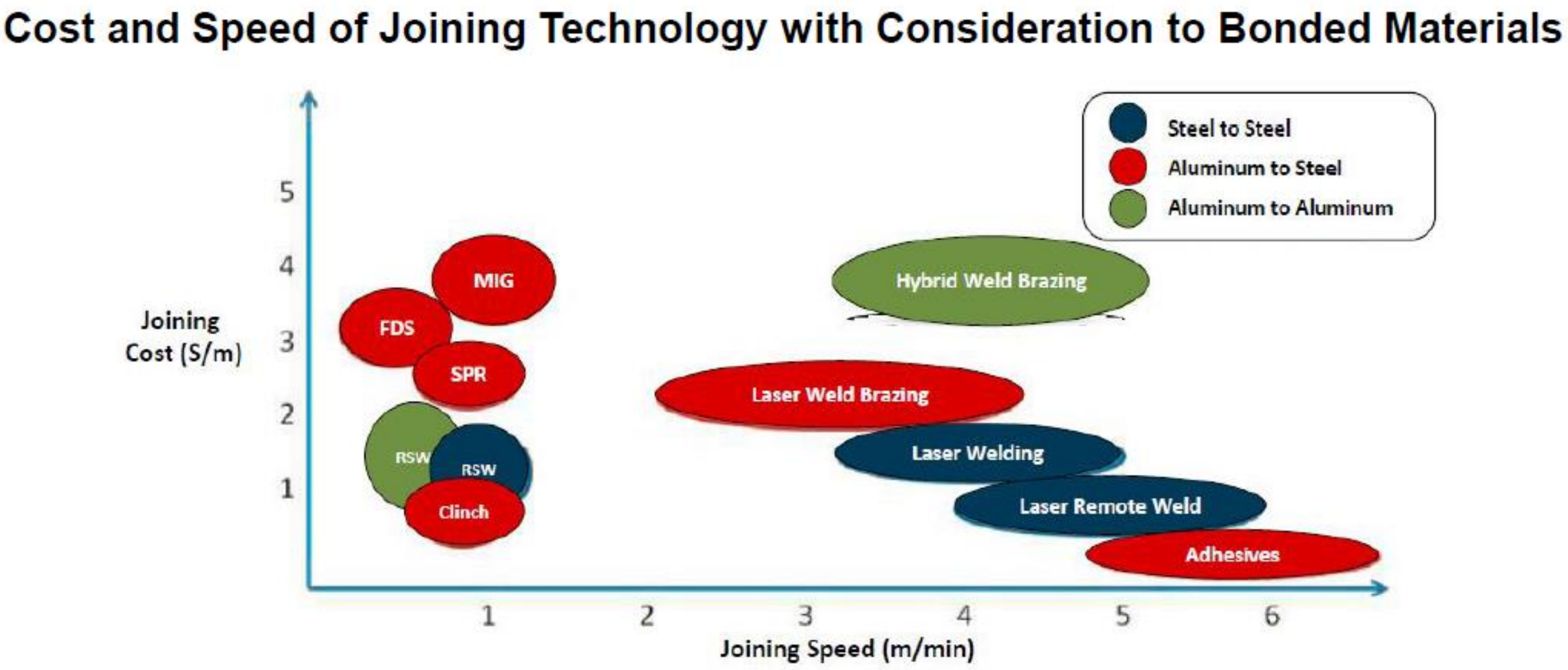
Automotive Joining Technologies

Automated Joining

- Reasons for automated joining
  - Speed/productivity
  - Increased quality/decreased variability
  - Reduction in direct labor required
  - Reduction in required floorspace
- Potential drawbacks
  - Parts need to be designed with automation in mind (joint accessibility, simple fit-up, tooling holes, appropriate tolerances, etc.)
  - Automation can have high up-front costs and determining the right balance of manual and automated tasks can be complex

Source: Atlas Copco

Joining Process Comparison



FDS: Flor Drill Screw, MIG: Metal Inert Gas, SPR: Self Piercing Rivet, FSW: Friction Stir Welding, RSW: Resistance Spot Welding

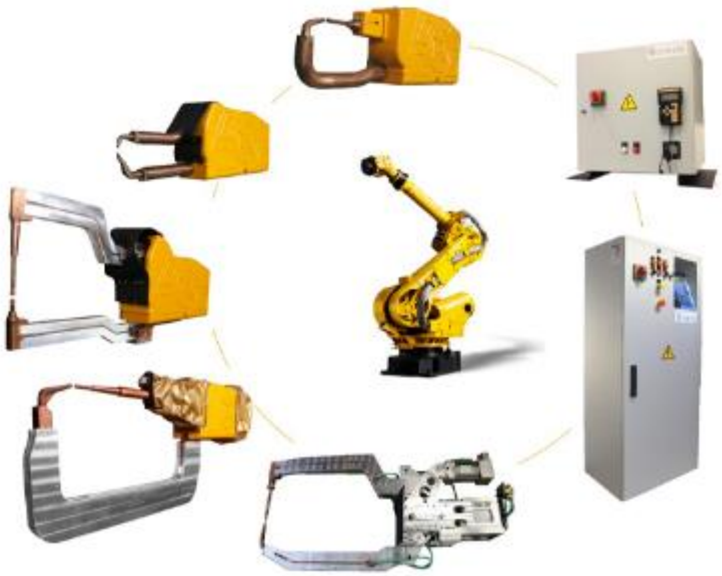
Crigui, I. B. "Robust Joining Processes for Series Production Today and Tomorrow." Innovative Developments for Light Weight Vehicle Structures. Wolfsburg: Volkswagon, 2009. 190.

Striking the Right Balance

- Ultimately, every product and project is at least a little unique. Differences in required annual volume, cycle time, available floor space, quality/performance requirements, labor availability, and many other items can shift the optimal balance point for automation.
- An integrator like Gonzalez can help inform the cost modeling exercise that must take place to optimize heliostat manufacturing for cost.

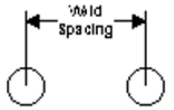
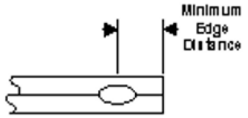
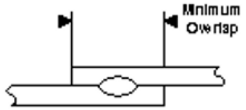
Spot Welding

- Spot welding is the primary joining method in automotive body structures, especially in steel bodies.
  - ~4 second cycle time per spot
  - Typical pitch of 30mm to 60mm in steel, up to 100mm in aluminum joints with adhesive
  - Requires 2-sided access to joint
  - Aluminum spot welding has become a mature technology



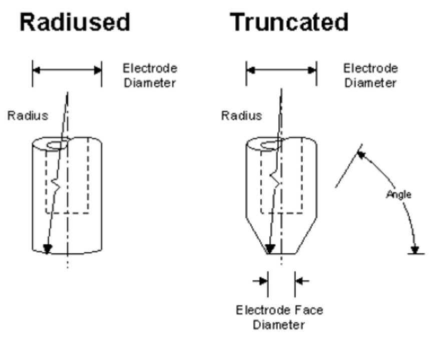
Source: ARO

Aluminum RSW Size, Spacing, Edge Distance & Overlap

	Metal Thickness (mm)	0.65	0.81	1.02	1.27	1.60	1.80	2.03	2.29	2.54	3.18
Minimum Weld Button Diameter (mm)	$4\sqrt{t}$	3.1	3.6	4.1	4.6	5.1	5.3	5.7	6.1	6.4	7.1
Recommended Weld Button Diameter (mm)	$5\sqrt{t}$	3.8	4.3	4.8	5.3	6.1	6.6	6.9	7.2	7.6	8.6
Minimum Weld Spacing (mm)		9.5	12.7		15.9		19.0		22.2	25.1	31.5
Minimum Edge Distance (mm)		5.6	6.4		7.9	9.5			11.1		12.7
Minimum Overlap (mm)		11.1	12.7	14.3	15.9	19.0	20.6	22.2	23.8	25.1	28.6

Ref: AA Welding Aluminum, Table 13.1

Parameter Guidelines for RSW Aluminum Sheet

	Metal Thickness (mm)	0.60	0.80	1.00	1.30	1.60	1.80	2.00	2.30	2.50	3.20
Radius (mm)		50.8		76.2						152.4	
Electrode Diameter (mm)		15.9								22.2	
Electrode Face Diameter (mm)		6.4			7.8		9.4			11.0	
Angle (Degree)		60					45				
Weld Force kN (lbs)	Radiused	3.6 (800)	4.0 (900)	4.5 (1000)			5.3 (1200)	6.2 (1400)	7.1 (1600)	8.0 (1800)	10.7 (2400)
	Truncated	2.2 (500)	2.5 (550)	2.7 (600)	3.1 (700)	3.8 (850)	4.1 (920)	4.6 (1040)	5.1 (1150)	5.6 (1250)	7.1 (1600)
Weld Time	Number of 60Hz Cycles	4			5	6	8		10		12
DC Welding Current kA RMS	As Received Surface	20	22	23	26	30	32	35	37	40	50
	Mechanical and/or Chemically Cleaned Surface	21	24	25	27	31	33	36	38	41	51

Ref: AA T10, Table 7

Typical Shear Strengths Requirements for Al

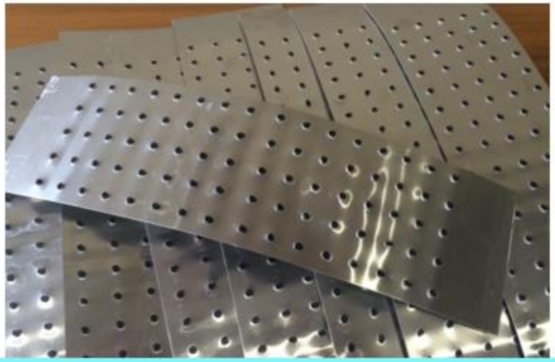
Shear Load Requirements for Spot Weld Sheet Specimens								
Group 1 Alloys - Aluminum and Magnesium Alloys								
Nominal Thickness of Thinner Sheet	Ultimate Strength 386 MPa and above		Ultimate Strength 240 MPa to 385.9 Mpa		Ultimate Strength 135 MPa to 239.9 Mpa		Ultimate Strength Below 135 Mpa	
	N per spot		N per spot		N per spot		N per spot	
mm	Min.	Min. Avg.	Min.	Min. Avg.	Min.	Min. Avg.	Min.	Min. Avg.
0.25	265	335	225	290	-	-	-	-
0.30	335	425	290	380	135	175	90	110
0.40	490	625	445	555	310	400	225	290
0.45	555	710	510	645	380	490	290	380
0.50	625	780	600	755	445	555	355	445
0.55	710	890	690	865	535	665	425	535
0.65	825	1045	780	890	645	825	490	625
0.70	995	1200	910	1155	780	980	600	755
0.80	1155	1445	1045	1310	935	1180	735	935
0.90	1355	1710	1225	1535	1135	1425	865	1090
1.00	1535	1935	1380	1735	1335	1670	1000	1270
1.10	1800	2270	1645	2070	1555	1955	1155	1445
1.30	2070	2600	1910	2400	1780	2225	1310	1645
1.40	2470	2980	2290	2870	2110	2645	1510	1890
1.60	2980	3635	2715	3400	2535	3180	1755	2200
1.80	3670	4605	3200	4005	2780	3600	2000	2515
2.00	4560	5715	3805	4760	3400	4270	2335	2935
2.30	5580	6985	4450	5560	3870	4850	2645	3315
2.50	6630	8295	5205	6515	4180	5225	3000	3660
2.80	7915	9895	5960	7450	4450	5580	3270	4090
3.20	9430	11785	7228	9050	4670	5850	3490	4380
3.60	11230	14055	8540	10675	-	-	-	-
4.10	13880	17345	10585	13565	-	-	-	-
4.60	16570	20730	13345	16680	-	-	-	-
4.80	17950	22440	14410	18015	-	-	-	-
6.40	32695	40920	28465	35585	-	-	-	-

Ref: AWS D17.2

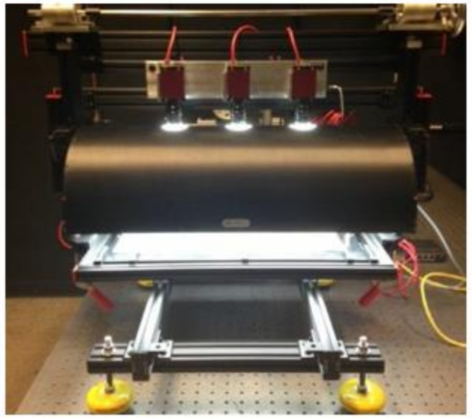
Arconic Capability to Test, Inspect, and Measure Unique to Industry

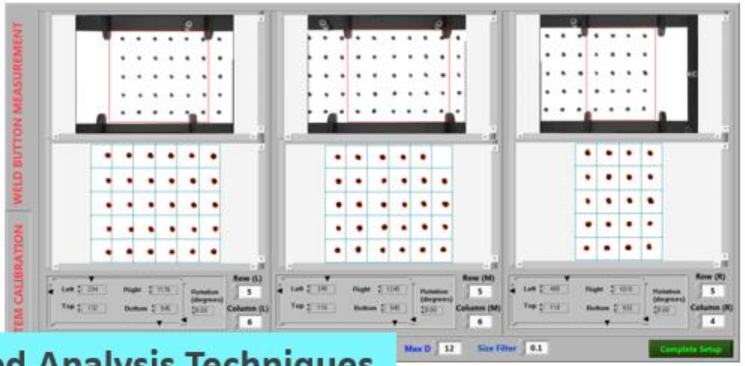
Robotic Pilot Line Testing

100% Peel Inspection



Automated Button Measurement





Full Scale Pilot Cell through Industry Leading Automated Analysis Techniques
Peel and Inspection Equipment Developed and Patented by Arconic

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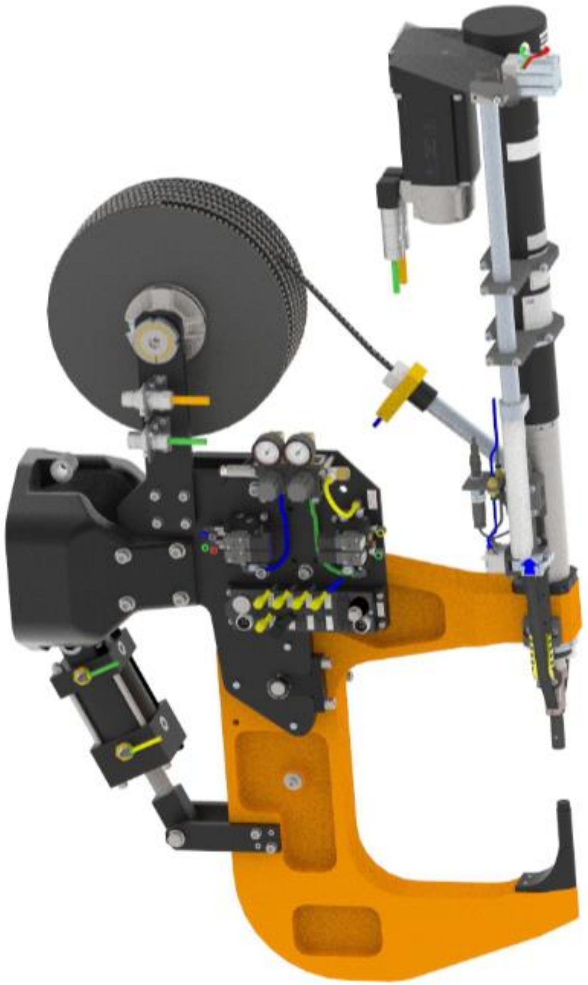
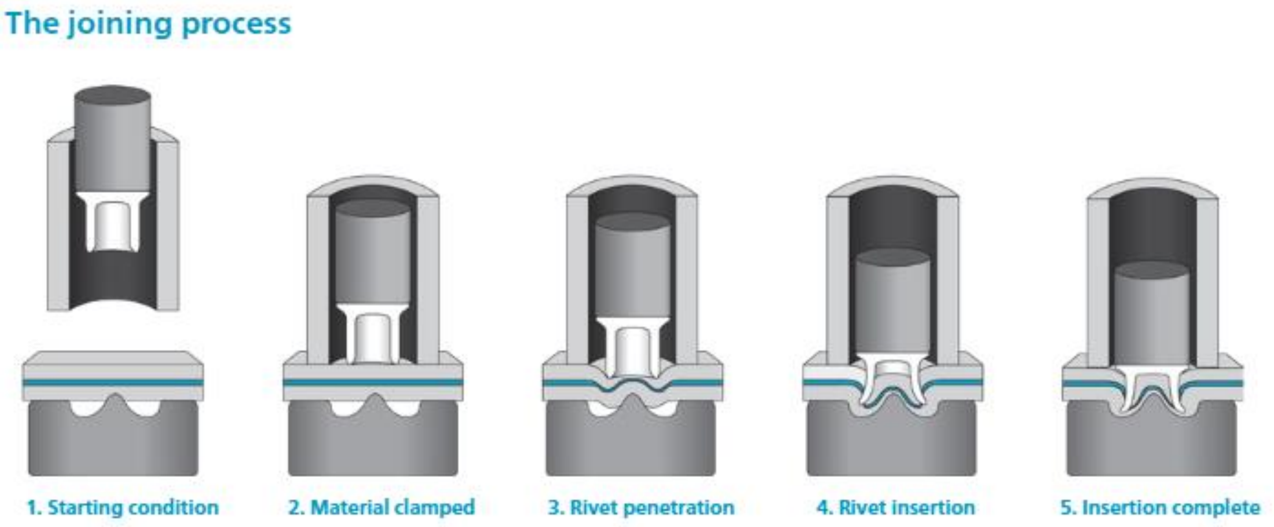
Self-Piercing Rivets

- Self-Piercing Rivets are another major joining method; heavily used in aluminum to aluminum or mixed material body construction.
  - ~5 second cycle time per rivet
  - Typical pitches range from 15mm minimum to 100+mm
  - Requires 2-sided access to joint

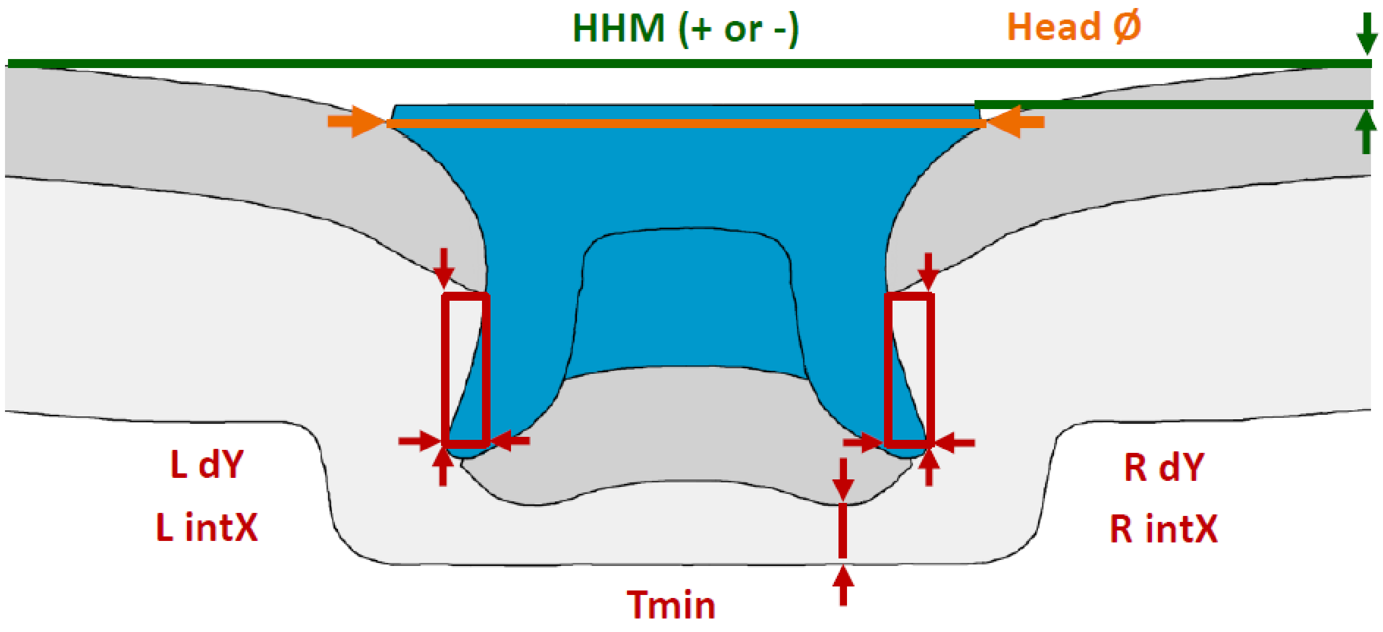


Source: Atlas Copco

Self-Piercing Rivets



Key	
HHM	Head Height Macro
Head Ø	Rivet Head Diameter
L dY	Left sided lockdepth in Y direction
L intX	Left sided interlock in X direction
R dY	Right sided lockdepth in Y direction
R intX	Right sided interlock in X direction
Tmin	Minimum bottom sheet thickness



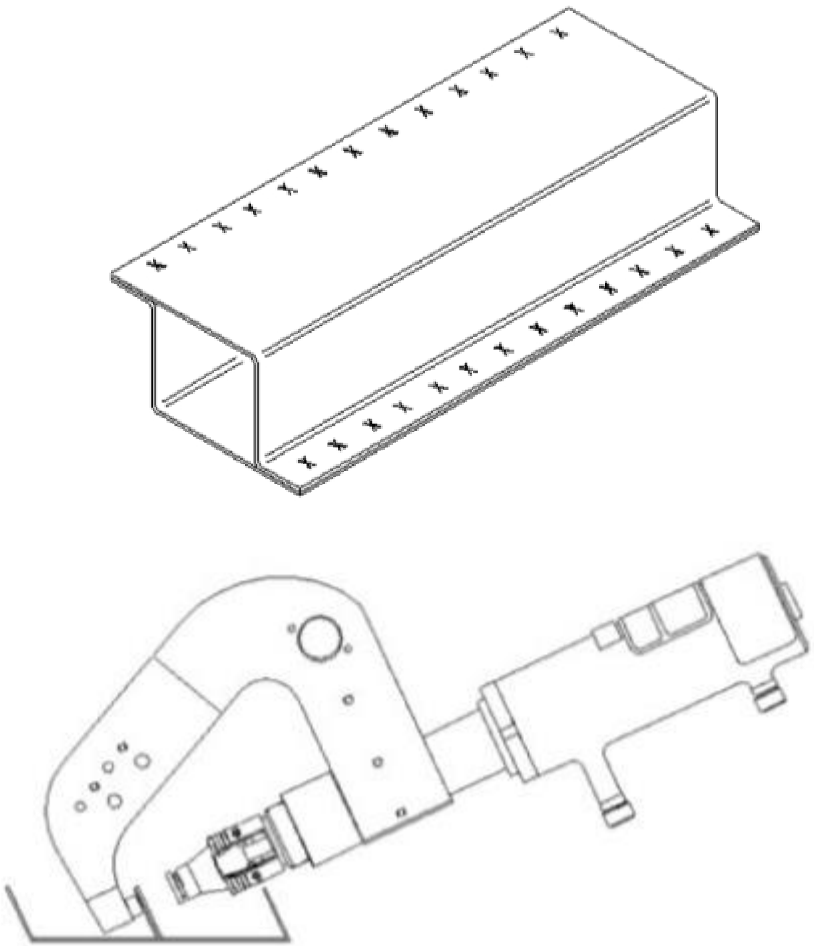
Example layout for macro inspection: 5mm C rivet in a 2 layer material stack

Source: Atlas Copco

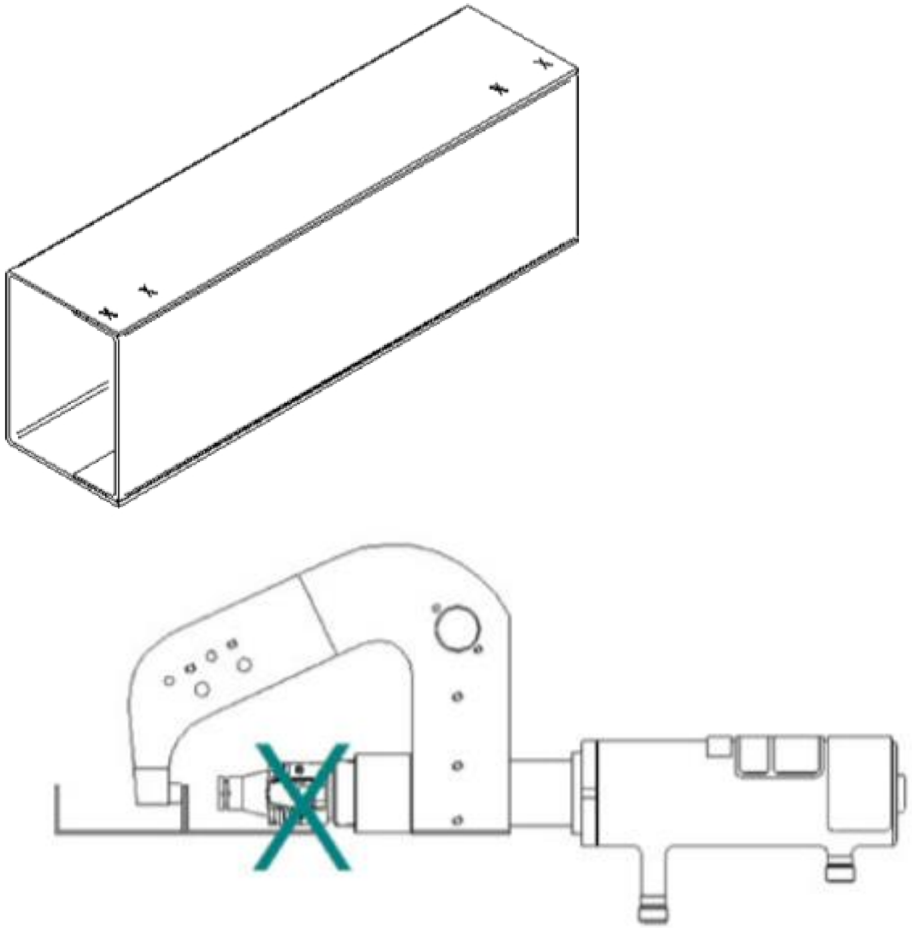
2-side access note

Avoid box sections that do not provide adequate tool access. The figure below contains examples of good and poor tool access.

Good Tool Access



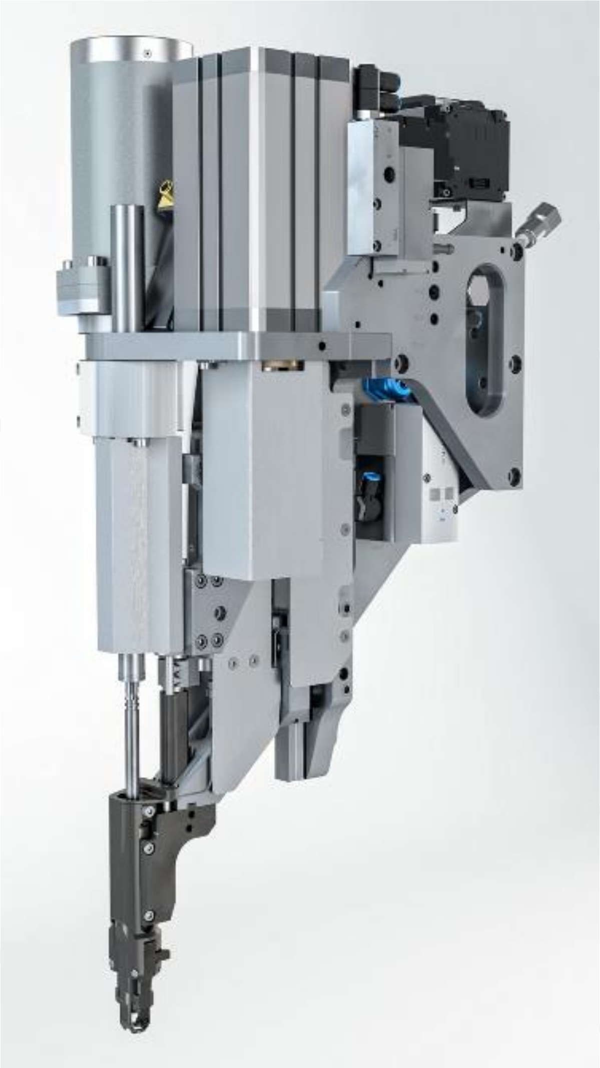
Poor Tool Access



Source: Atlas Copco

Flow Drill Screws

- Flow drill screws provide fast, strong joining with single-side access.
  - ~6 second cycle time per screw
  - Typical pitches range 20mm minimum to 100+mm
  - Requires 1-side access to joint, sometimes with backup on opposite side for stiffness



Source: Atlas Copco

Flow Drill Screw

The joining process

1. Positioning

The fastener is positioned on the workpiece and rotated at high speed. This heats up the material

2. Penetration

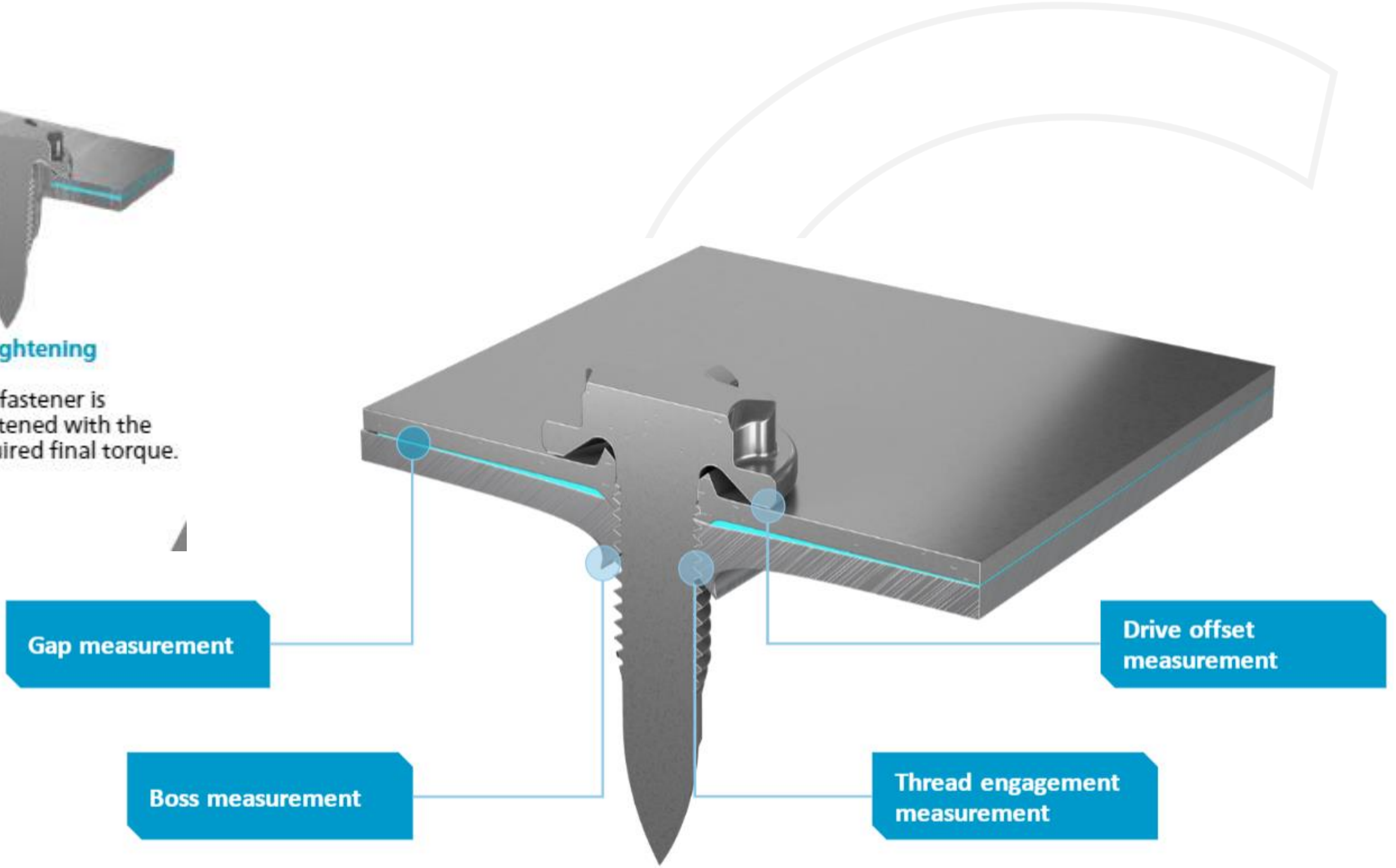
With high rotation speed and high force, the fastener is pushed through the material layers.

3. Thread forming

With reduced speed and process force, the fastener forms a thread without cutting.

4. Tightening

The fastener is tightened with the required final torque.



Source: Atlas Copco

Adhesives

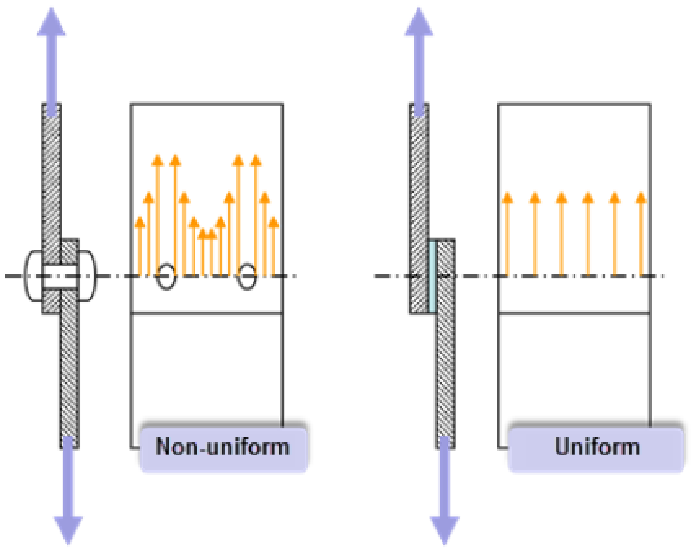
- Adhesives provide high-speed joining for a multitude of materials and have a very wide variety of properties and curing options available.
  - Dispense speeds often range from 200-300+mm/s
  - Provides isolations between dissimilar metals
  - Large bond areas provide enhanced stiffness and reduced stress concentrations versus discrete fasteners
  - Pair well with spot-welds, self-piercing rivets, and flow drill screws for hybrid joints

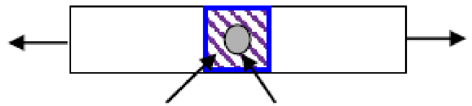
Source: Atlas Copco

Adhesives

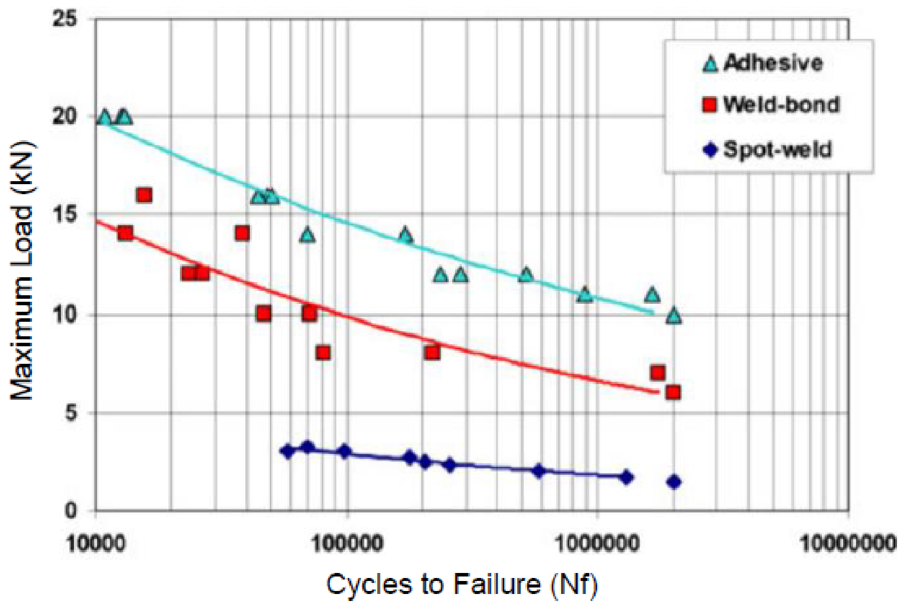
Results in enhanced **stress distribution** and **durability** of joints

Elimination of stress concentration





Increased load-carrying capability

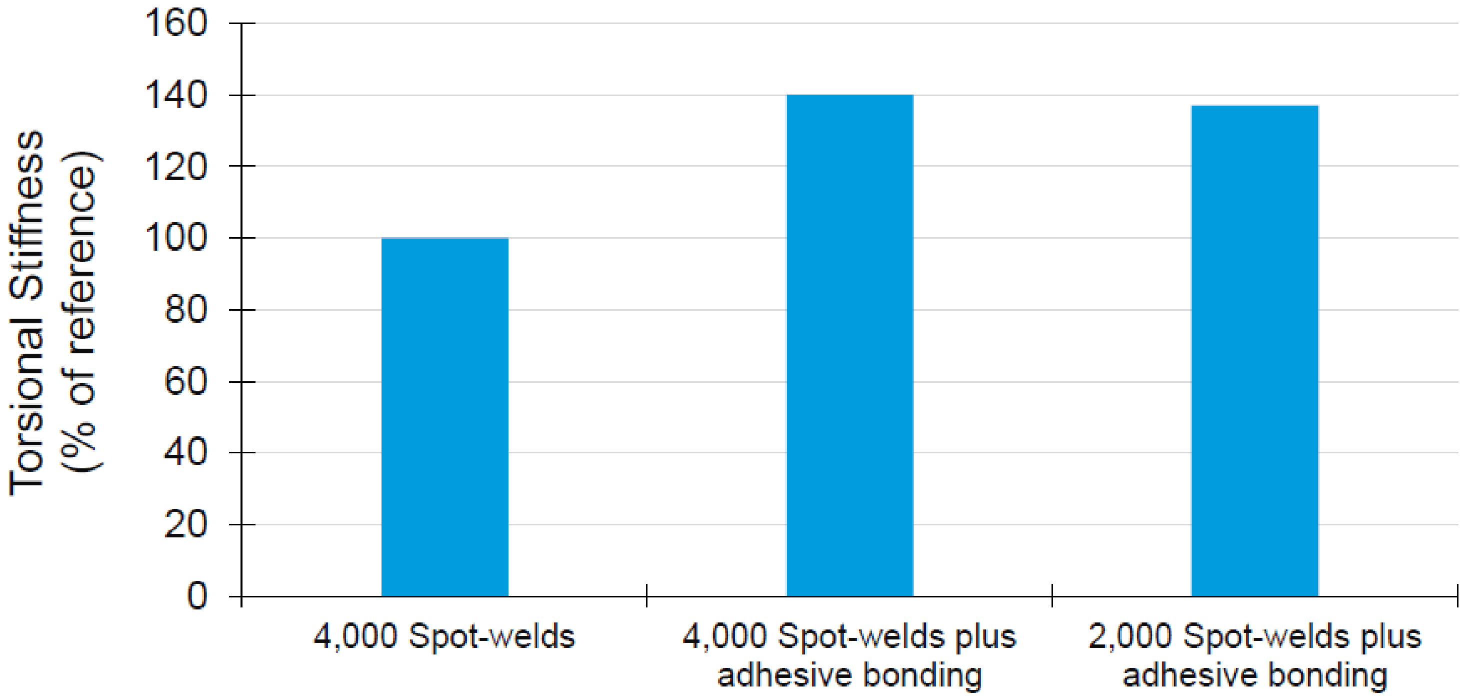


Chang et *al*. "Studies on the stress distribution and fatigue behavior of weld-bonded lap shear joints" *J. Mater. Process Technol.* **2001**, *108*, 307 - 313
Smtih et *al*. "Structural performance of adhesive and weld-bonded joints in AHSS" *Weld World* **2013**, *25*, 147 - 156

Adhesives

Strength improvements resulting from adhesive bonding also afford **downgauging and spot-weld reduction.**

Eliminating spot-welds reduces production cost and process time.

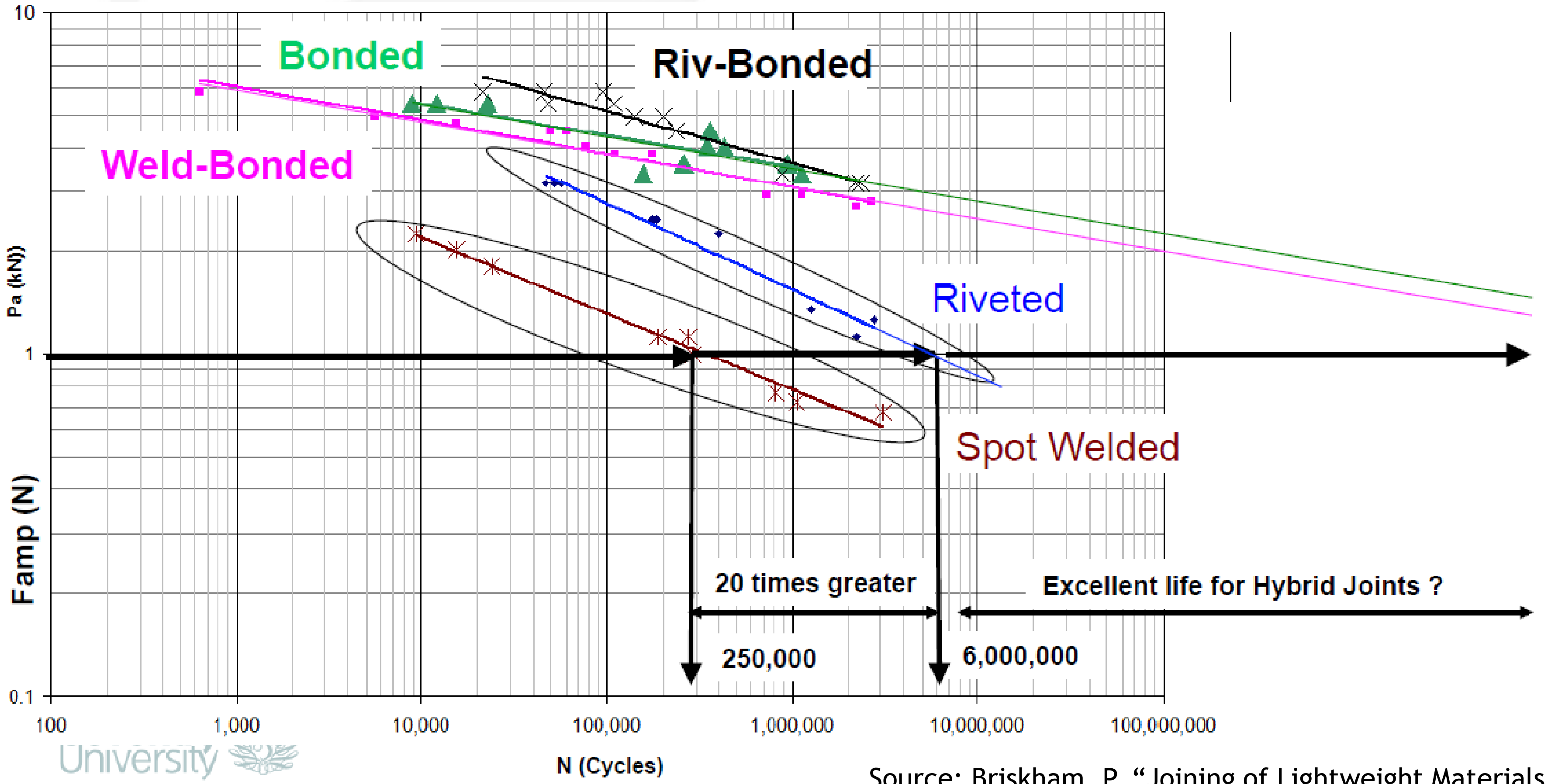


Symietz, D."Strength in Unity" *Euro. Coatings J.* **2006**, *12*. 46 - 50

DUPONT

Fatigue Performance

- Cars are exposed to cyclic loads in service and the fatigue life of joints is equally as important as the quasi static strength.
- Riveted joints usually have longer fatigue life than spot welded joints.
- Bonded hybrid joints offer excellent fatigue life at low loads.
- Bonded joints usually have a flatter FN curve making failure harder to predict.



University

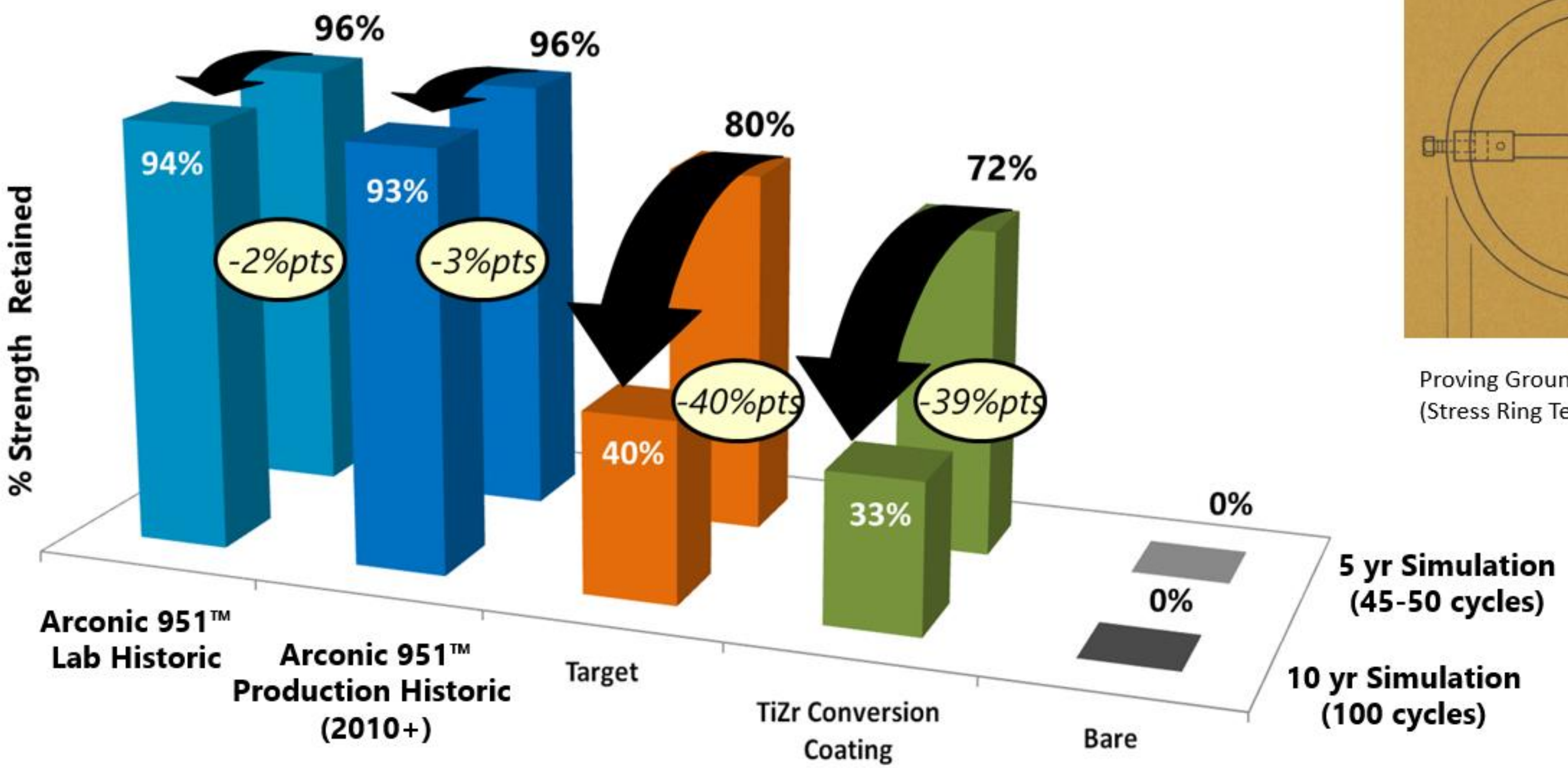
Source: Briskham, P. "Joining of Lightweight Materials with Adhesives and Fasteners for Automotive Applications" Forming, Joining & Tooling Session London Business Conferences 2012

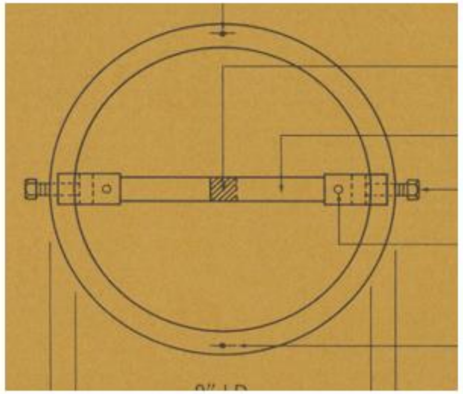
Aluminum and Adhesives

- The natural oxide layer that forms on aluminum complicates adhesive use as well as welding – bond prep is critical
- In automotive body applications, the aluminum is sourced with a pre-treatment (Arconic A951 or TiZr coatings) that gives a repeatable, predictable surface that resists various mechanisms of adhesive bond degradation.
- Adhesives that tolerate mill oils and stamping lubricants are used to facilitate bonding without manual preparation.
- Other methods, such as laser ablation, create a repeatable and clean surface without the added cost of the pretreatments.
- Adhesives are a critical enabler of other joining methods such as spot welding and riveting.

Aluminum Pretreatments

Arconic 951™ is 4X to 9X Stronger than TiZr





Proving Ground Simulation Exposure
(Stress Ring Test)

Demonstrated superior bond durability performance across OEM customer base (highest retained strength in use)

ARCONIC

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Thomas Mataloni, Kerry Kubena, and Russell Long at Arconic

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Matthew Taylor and Ray Bis at Dupont

Thank you for your time and consideration

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