Aalto University
School of Engineering

Department of Engineering
Design and Production

Engineering Materials

DEVELOPMENT OF FSW PARAMETERS FOR AZ31 MECHANICAL AND CORROSION PROPERTIES

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SVETS Kommissionen
AG 52 FSW Processing

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Aalto University, Finland

Objectives (1/2)

- Overall
  - To develop the know-how and investigate the feasibility of joining Mg alloys to apply in new concept chassis for automotive seats

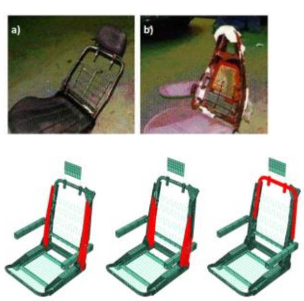
- Reduction in weight
  - Energetic fuel saving
  - Reduction in CO_2 emissions
- Reduction in cost
  - Minimization of base material consumption
  - Minimization manufacturing and assembling time

Objectives (2/2)

☞ Present Study

- To evaluate the weldability by FSW of Mg alloy AZ31 in a representative plate thickness for application in automotive seats
- To establish the welding lobe and determine the best values for the most relevant FSW parameters supported by global efficiency factors based on tensile, bending and hardness distribution
- To assess for joints with best set of FSW parameters:
  - ✓ metallurgical features
  - ✓ resistance to fatigue loading
  - ✓ corrosion behaviour

Motivation (1/3)



☞ **Seat weights:**

- ✓ 13 – 20 kg - lower car segments
- ✓ 35 – 50 kg – higher car segments

☞ **Car weight:** 900 – 1800 kg

Total weigh of seats in a car can range from 5% to 11% of total car weight

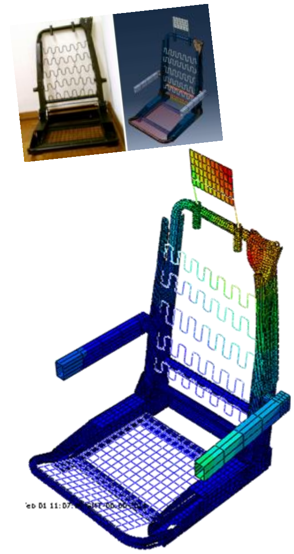
☞ **Other important features:**

- ✓ Closest feature to the person
- ✓ Structure that focus on safety and comfort
- ✓ Very small maintenance level

Motivation (2/3)

☞ **Overview of Structural Analysis Results**

- Test according to automotive standards (e.g. with application of a predefined force of 13.5 kN, without exceeding max displacement e.g. Δ_{max} = 178 mm)
- It was analysed the replacement of several materials e.g. i) Al alloys; ii) Mg alloys; iii) Carbon and iv) Glass Fiber Reinforced Composite *versus* Steel
- Mg alloys had similar performances to Steel
- Weight savings can go from 20% up to 60% by replacing the metallic structure of the seat while complying with automotive regulations



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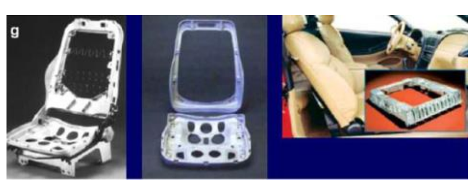
Motivation (3/3)

☞ **Solution:** Replacement of current metals with lighter alloys

- ✓ Magnesium is a very light alloy (ρ = 1750 kg/m^3)
- ✓ Has a good castability allowing the casting of complex shapes



M.K.Kulekci, "Magnesium and its alloys applications in automotive industry," Int.J.Adv.Manuf.Technol., 39, 851–865, 2007.

☞ **Challenge**

- ✓ Current joining methods present several difficulties
- ✓ Critical corrosion susceptibility
- ✓ FSW is a good method for similar and dissimilar joints with Mg alloys

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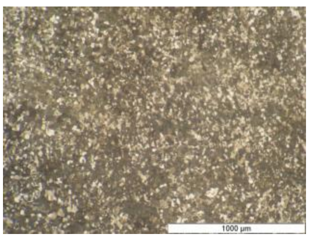
Experimental Conditions (1/2)

Base Material Characterization

AZ31 (hexagonal close packed - HCP) [wt.%]

Plate thickness = **2 mm**

Mg	Al	Zn	Mn (min)	Si (max)	Cu (max)	Fe (max)	Ca (max)	Other (max)
Bal.	**2.5–3.5**	**0.6–1.4**	0.2	0.1	0.05	0.005	0.4	0.005



Tensile Properties

E = 45 GPa

σ_{yield} = 155 MPa

σ_{max} = 252 MPa

A = 17 %

Toughness (U_t) = 42 kJ/mm^3

Hardness Properties

Hardness = 74 HV05

3pt Bending Properties

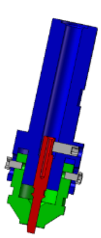
F_{max} = 2.1 kN

d = 5.5 mm

Energy (En) = 9 kJ

Experimental Conditions (2/2)

FSW Experimental Condition



Tool Features	
Probe	Conical 4:3 with variable length Threaded ISO M4
Shoulder	$\varnothing_{ext}$ = 15 mm ; $\varnothing_{int}$ = 4 mm Plane + 2 scrolls (pitch=1)
Photo	

Plan for Optimization of FSW Parameters (1/3)

Taguchi Method

FSW parameters	Symbol	Level 1	Level 2	Level 3
Variable parameters				
Vertical forging force, F_z [kgf]	**A**	400	450	500
Travel speed, v [mm/min]	**B**	100	200	400
Length of the probe, L_{probe} [mm]	**C**	2.08	2.17	2.25
Constant value parameters				
Tilt angle	0°			
Spindle rotation (direction)	1200 rpm (CW)			
Plunge speed	0.1 mm/s			
Dwell time	6 s			
Type of weld period process control	Force control			

3 Parameters at 3 Levels

⇩

Matriz L_9

Plan for Optimization of FSW Parameters (2/3)

Taguchi Method: Performance Parameters

$$GET = C_E \frac{E_i}{E_{BM}} + C_{\sigma_{0,2}} \frac{\sigma_{0,2_i}}{\sigma_{0,2_{BM}}} + C_{\sigma_{max}} \frac{\sigma_{max\,i}}{\sigma_{max\,BM}} + C_A \frac{A_i}{A_{BM}} + C_U \frac{U_i}{U_{BM}}$$

GET		GEB	
C_E	0.10		
$C_{\sigma_{0,2}}$	0.30	$C_{F_{max}}$	0.25
$C_{\sigma_{max}}$	0.30	$C_{d_{F_{max}}}$	0.25
C_A	0.15	$C_{En_{F_{max}}}$	0.50
C_U	0.15		

$$GEB = C_{F_{max}} \frac{F_{max\,i}}{F_{max\,BM}} + C_{d_{F_{max}}} \frac{d_{F_{max\,i}}}{d_{F_{max\,BM}}} + C_{En_{F_{max}}} \frac{En_{F_{max\,i}}}{En_{F_{max\,BM}}}$$

$$Hard = \frac{HV_{min}}{HV_{BM}}$$

Plan for Optimization of FSW Parameters (3/3)

Implementation of the Taguchi Method

$$\uparrow \frac{\Omega}{v}(=12)$$

Hotter conditions

Colder conditions

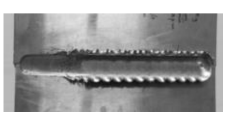
$$\downarrow \frac{\Omega}{v}(=3)$$

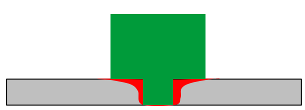
Taguchi Matriz L_9

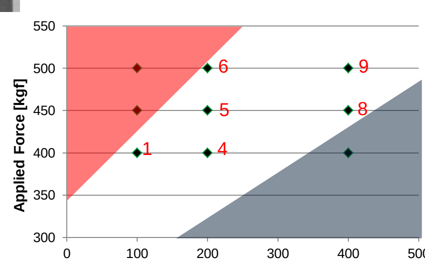
Trial	v [mm/min]	F_z [Kgf]	L_{probe} [mm]
1	100	400	2.08
2	100	450	2.17
3	100	500	2.25
4	200	400	2.17
5	200	450	2.25
6	200	500	2.08
7	400	400	2.25
8	400	450	2.08
9	400	500	2.17

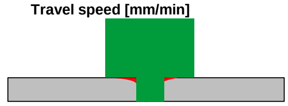
FSW Technological Limit Conditions (1/3)

Welding Lobe: Defective "Hot" and "Cold" Conditions Zones



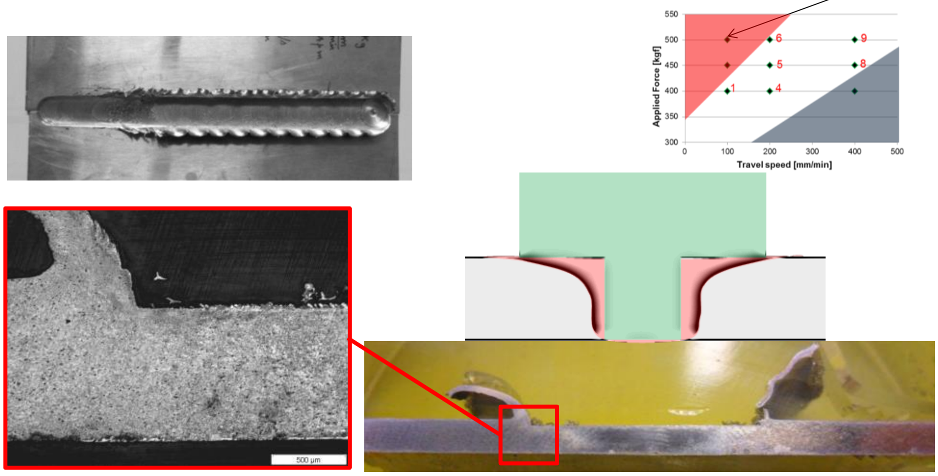






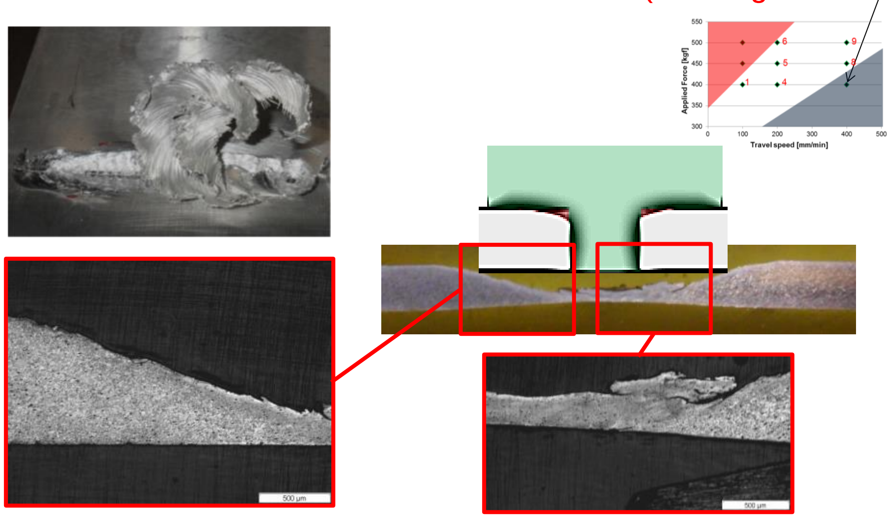
FSW Technological Limit Conditions (2/3)

Defect Mechanism: “Hot Conditions” + High Fz (=500 kgf - Trial 3)



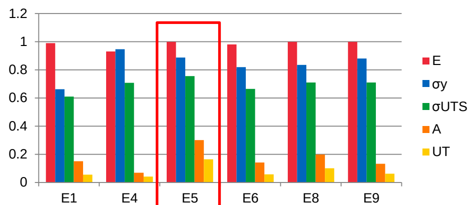
FSW Technological Limit Conditions (3/3)

Defect Mechanism: “Cold Conditions” + Low Fz (=400 kgf - Trial 7)



Analysis of the Performance Parameters (1/3)

Tensile Resistance: **GET**

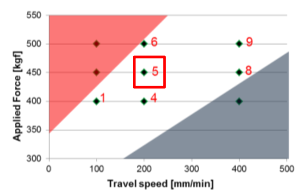


E1	E4	E5	E6	E8	E9
51.2%	60.6%	**66.3%**	57.4%	60.8%	60.7%

Trial E4

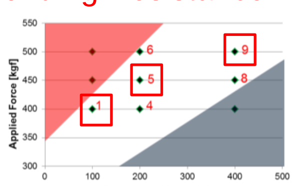
Trial E9

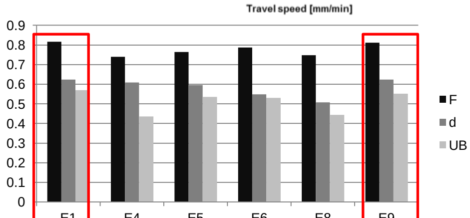
Trial E5



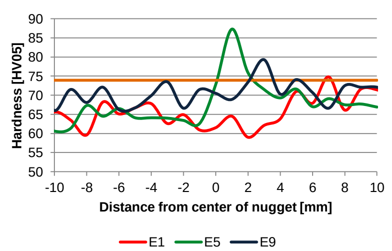
Analysis of the Performance Parameters (2/3)

Bending Resistance: **GEB** + Hardness: **HARD**

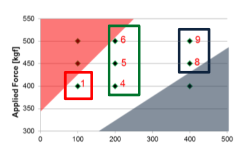




E1	E4	E5	E6	E8	E9
64.5%	55.4%	60.7%	59.9%	53.6%	63.5%



E1	E4	E5	E6	E8	E9
76%	80%	82%	81%	86%	89%



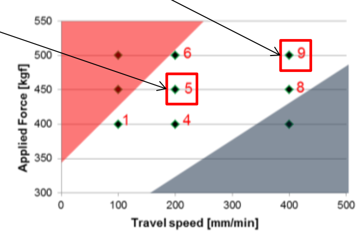
Analysis of the Performance Parameters (3/3)

Global Efficiency Analysis

[%]	E1	E4	E5	E6	E8	E9
GET	51	61	66	57	61	61
GEB	64	55	61	60	54	63
HARD	76	80	82	81	86	89
GLOBAL	**60.3**	**60.0**	**65.1**	**56.3**	**59.8**	**64.9**

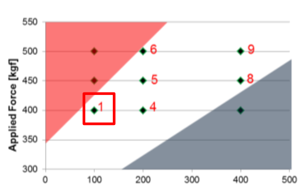
$$GLOBAL = C_{GET}.GET + C_{GEB}.GEB + C_{HARD}.HARD$$

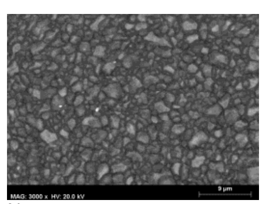
40% 50% 10%



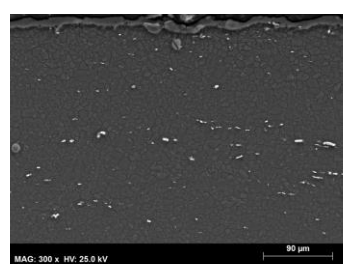
Metalographic Results (1/3)

Hot Weld Condition: Trial E1



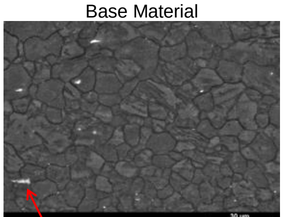


Nugget

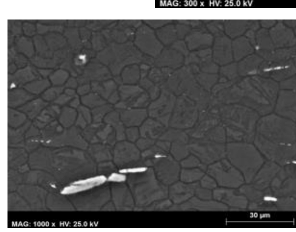


HAZ

Base Material



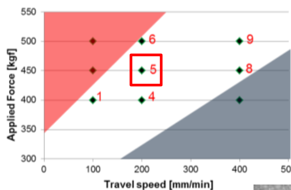
Al-Mn particles - corrosion initiators
(low particles density in this sample)

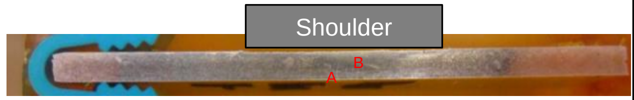


Detail of HAZ

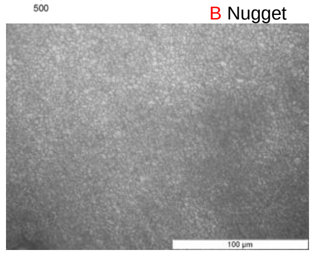
Metalographic Results (2/3)

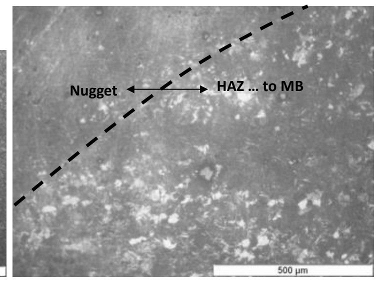
The Best Condition: Trial E5



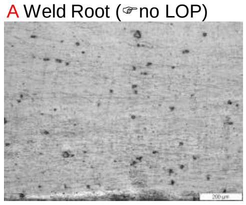


B Nugget



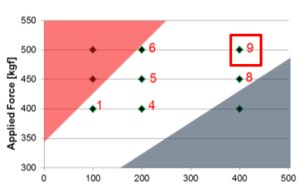


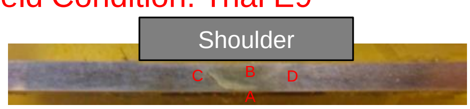
A Weld Root (☞no LOP)

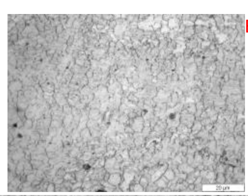


Metalographic Results (3/3)

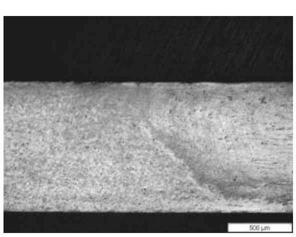
Cold Weld Condition: Trial E9



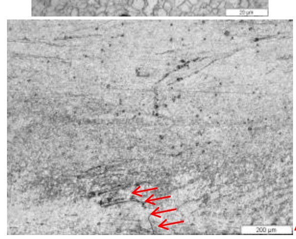




B Middle of Nugget

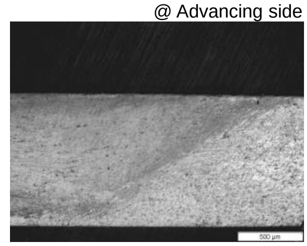


C Interface HAZ/Nugget
@ Retreating side



A Weld Root (☞LOP)

D Interface Nugget/HAZ
@ Advancing side

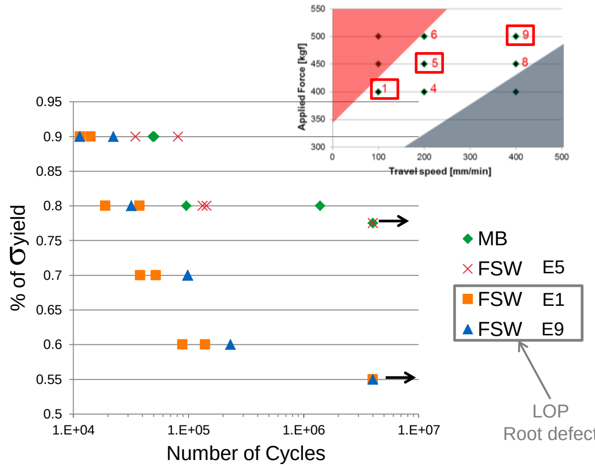


Fatigue Testing

Base Material and Selected Representative Trials

Fatigue testing conditions

- ✓ ASTM E 466-96 “Standard practice for conducting force controlled constant amplitude axial fatigue tests of metallic materials”
- ✓ F = 15 Hz
- ✓ R = 0.1
- ✓ BM: σ_{yield} = 155 MPa
- ✓ FSW: σ_{yield} = 140 MPa

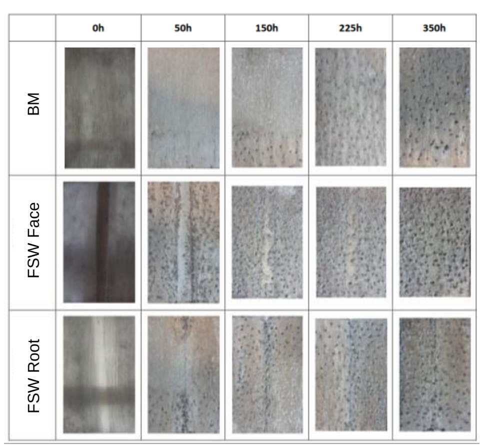


Corrosion Testing (1/2)

Saline Environment (ASTM B117:95)

Experimental procedure

- ✓ Saline environment (**5%NaCl**) until **350h** period or until extreme corrosion that damaged the part was encountered



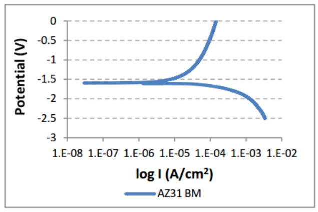
Sample	MB	Travel speed [mm/min]		
		100	200	400
[wt. %] Corroded	3.10	9.26	5.77	3.69

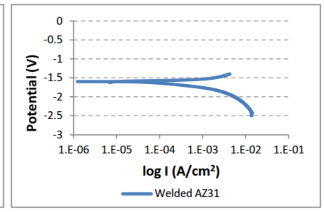
Corrosion Testing (2/2)

Electrochemical tests (ASTM G102:89)

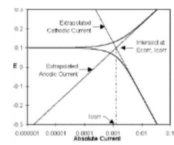
☞ Objective: To understand the corrosion mechanisms affecting these alloys during the saline testing

✓ Polarization Curves:





Note: The polarization curves are composed by the anodic oxidation curve and the cathode reduction curve



☞ Corrosion Rate (CR) calculation based on Faraday's Law :

Material	icor (μA/cm²)	Ecor (V)	EW [130]	CR (mm/year)
AA5754	2.905E-1	-0.786	9.09	3.14E-03
AA6082	4.923-1	-0.732	8.98	5.26E-03
AZ31 BM	1.138	-1.597	12.15	2.58E-02
AZ31 Welded	1.518	-1.580	12.15	3.45E-02

Conclusions (1/2)

- The weld lobe of the 2 mm plates of AZ31 by FSW was established and the mechanisms of defective conditions for Hot and Cold conditions were presented
- The best FSW parameters were established for Intermediate conditions resulting in no LOP, reaching a GET=66 % ; GEB=61 % ; Hard Loss=82 %, corresponding to an overall static efficiency of 65 %
- Best developed FSW conditions resulted in a fatigue limit of about 0.8 x σ_{yield} and similar to the base material behaviour

Conclusions (2/2)

- The corrosion tests in saline environment shown that corrosion level increases from cold to hot welds and is mainly localized in the HAZ. The best set of parameters resulted in an increase of about 86 % relative to base material. The root of the welds are also preferential location for corrosion activity
- The polarization curves enabled a corrosion rate prevision for the welded zone of about 35.4 μm/year, and 34 % higher than for base material