Metallurgy and Friction Stir Welding

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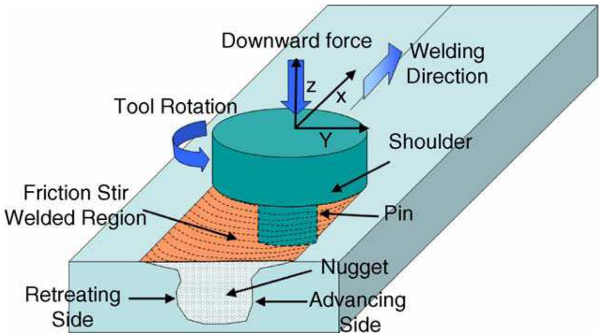
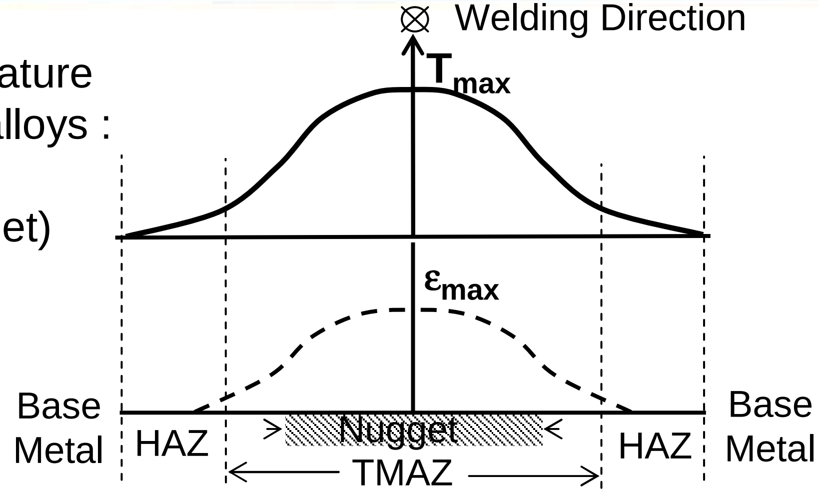
return on innovation

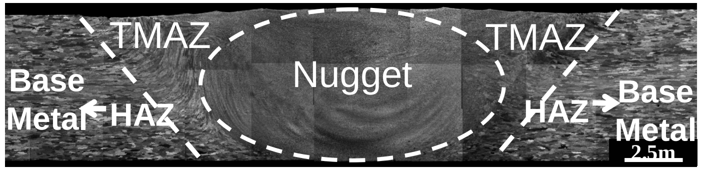
Basics of the FSW Process



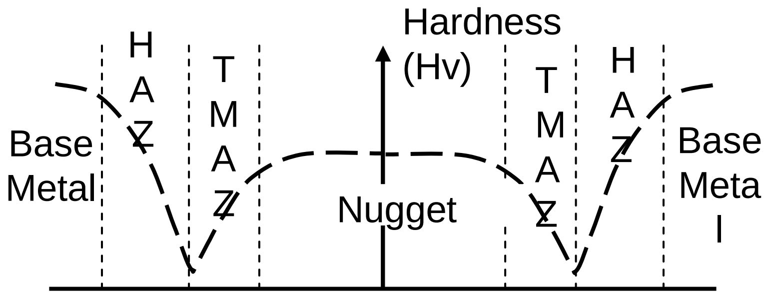
From Mishra and Ma,. Materials Science and Engineering R 50 (2005)

Typical temperature domain for Al alloys :
200℃ (HAZ)
to 500℃ (Nugget)





Microstructural and related hardness evolution resulting from thermal cycle and strain encountered during Friction Stir Welding

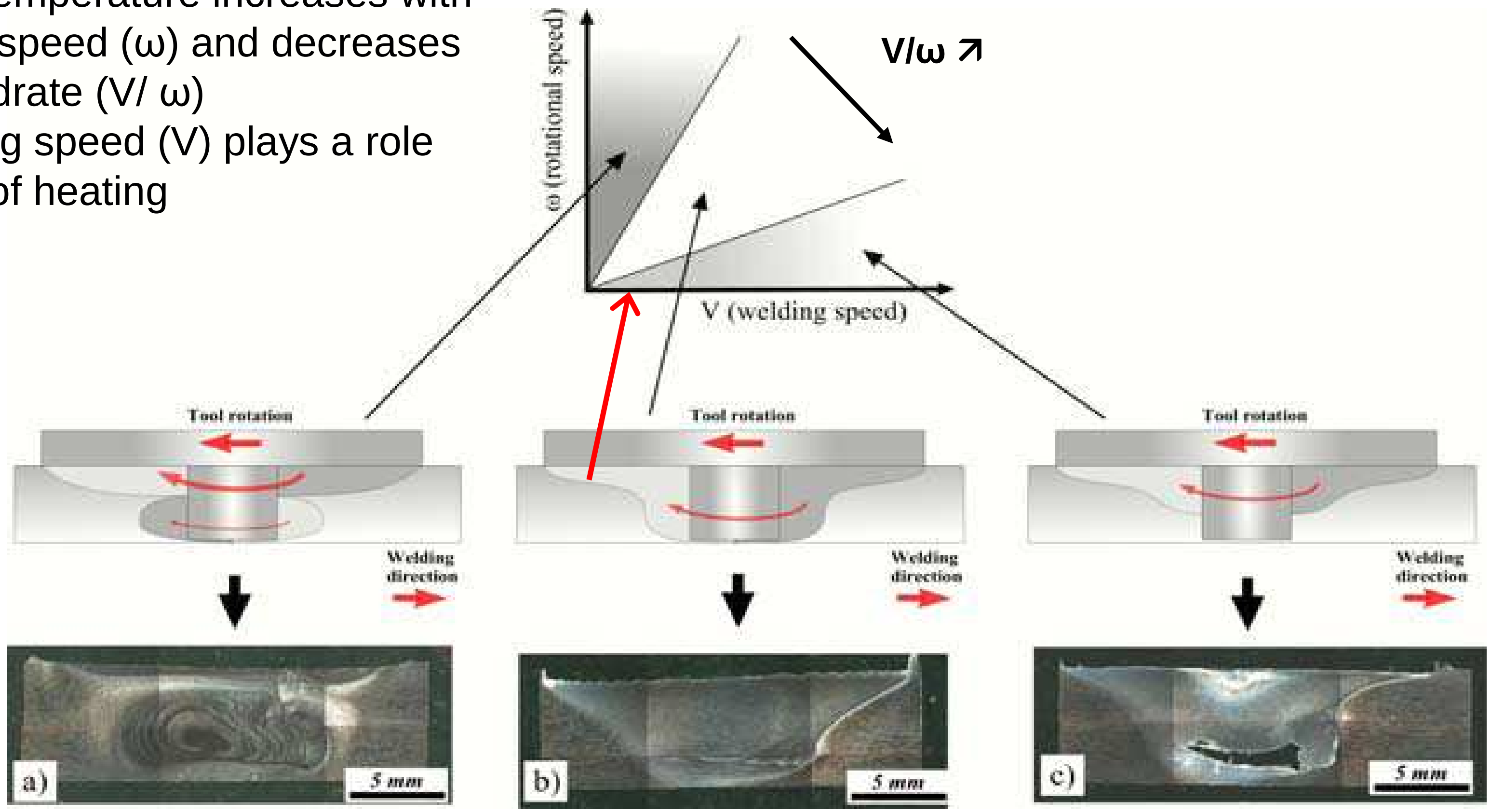


6056-T78 FSW (from Gallais et al., Met Trans (2007) 38A)

Process window for FSW of Al alloys

General trends :

- Peak temperature increases with rotation speed (ω) and decreases with feedrate (V/ ω)
- Welding speed (V) plays a role on rate of heating



Weld quality as function of feed ratio, FSW of AA6061

(Dubourg, et al. 6th Int. FSW Symp., St Sauveur, Canada, 2006).

The undermatching of FS welds

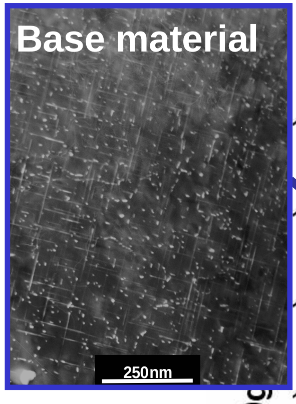
- The weak zone of the weld is governed by the microstructural evolution through the weld

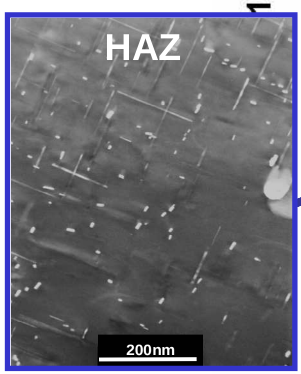
In the case of aluminium alloys, two extreme cases have to be considered :

  - precipitation-hardenable alloys
    (2XXX, 6XXX and 7XXX alloys)

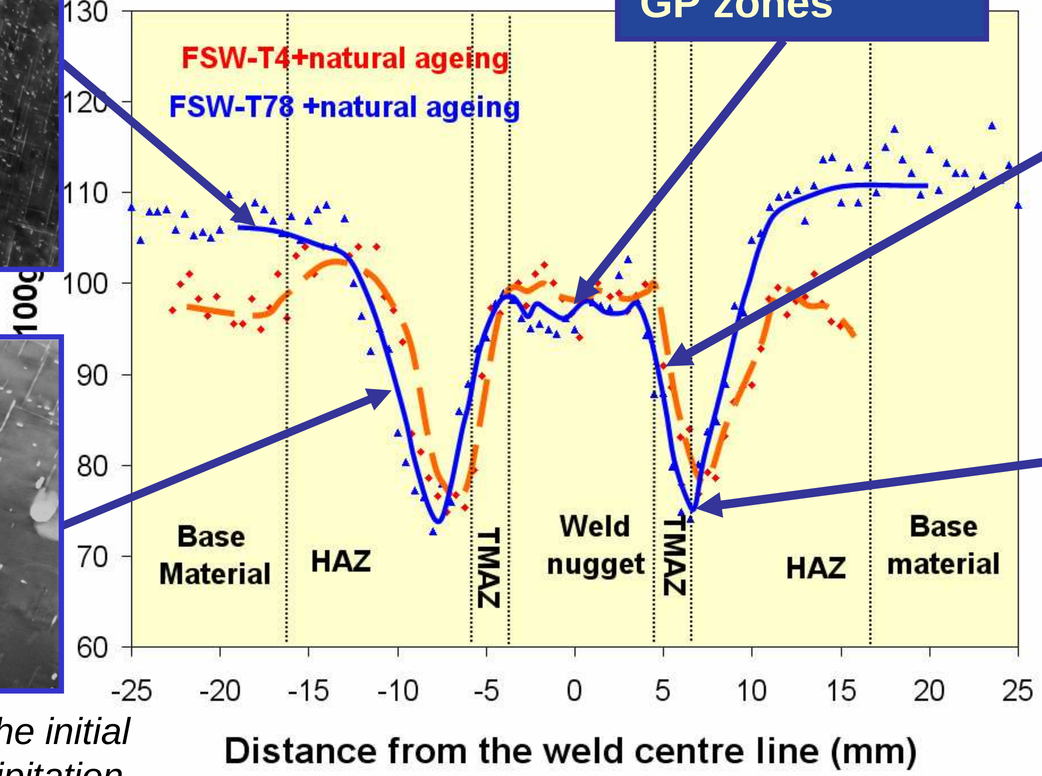
  - solid-solution or work-hardened alloys
    (5XXX alloys)

Heat treatable alloys : the case of precipitation hardened alloys

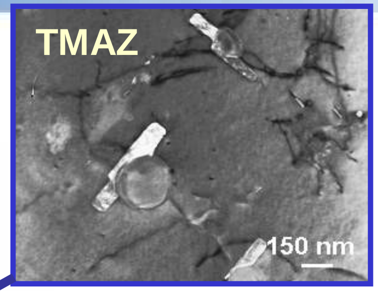




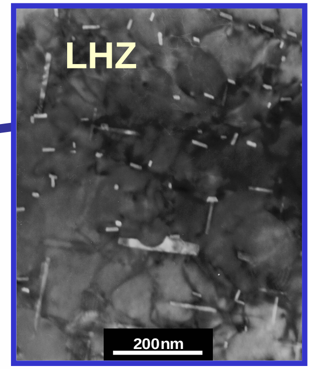
Coarsening of the initial hardening precipitation



Weld nugget :
No precipitation
GP zones



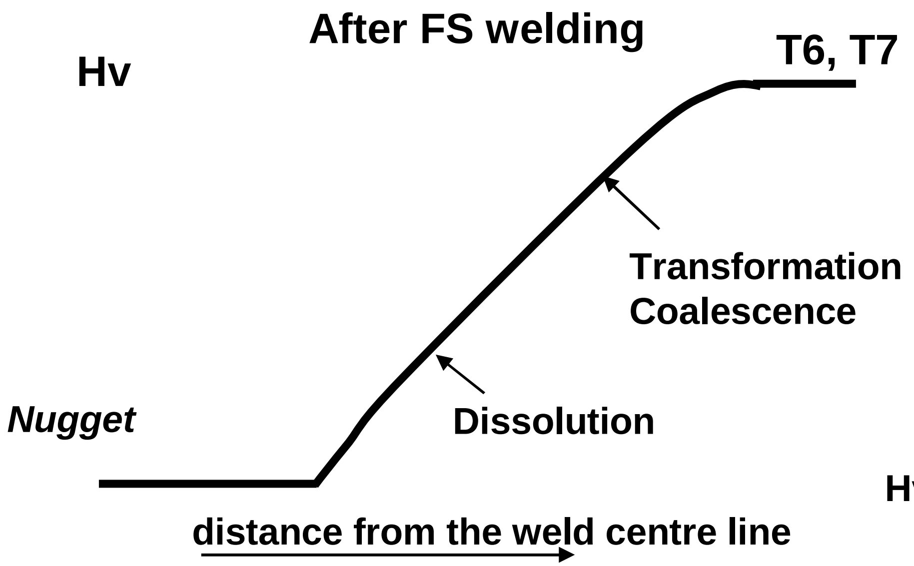
Coarsening and dissolution of the initial hardening precipitation



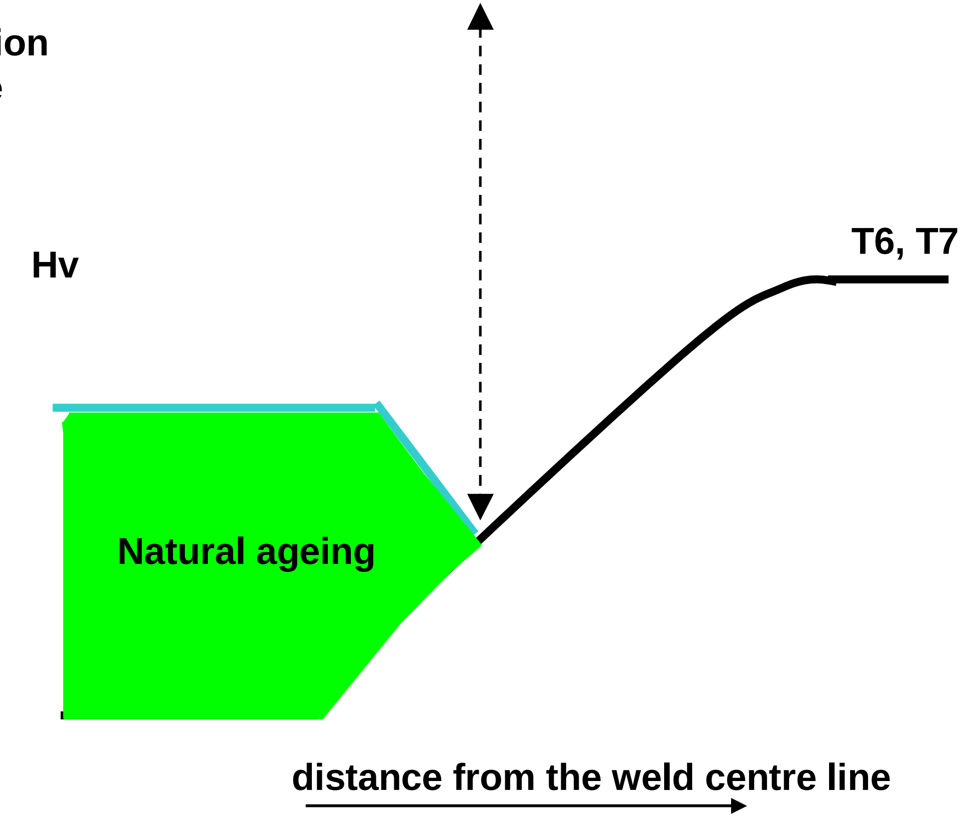
Coarsening of the initial hardening precipitation

FSW of 6056-T78 : Weakest zone near the TMAZ/HAZ interface due to the coarsening of initial precipitates *(Denquin et al., Mater. Sci. Forum 3 (2002)).*

Heat treatable alloys : the case of precipitation hardened alloys

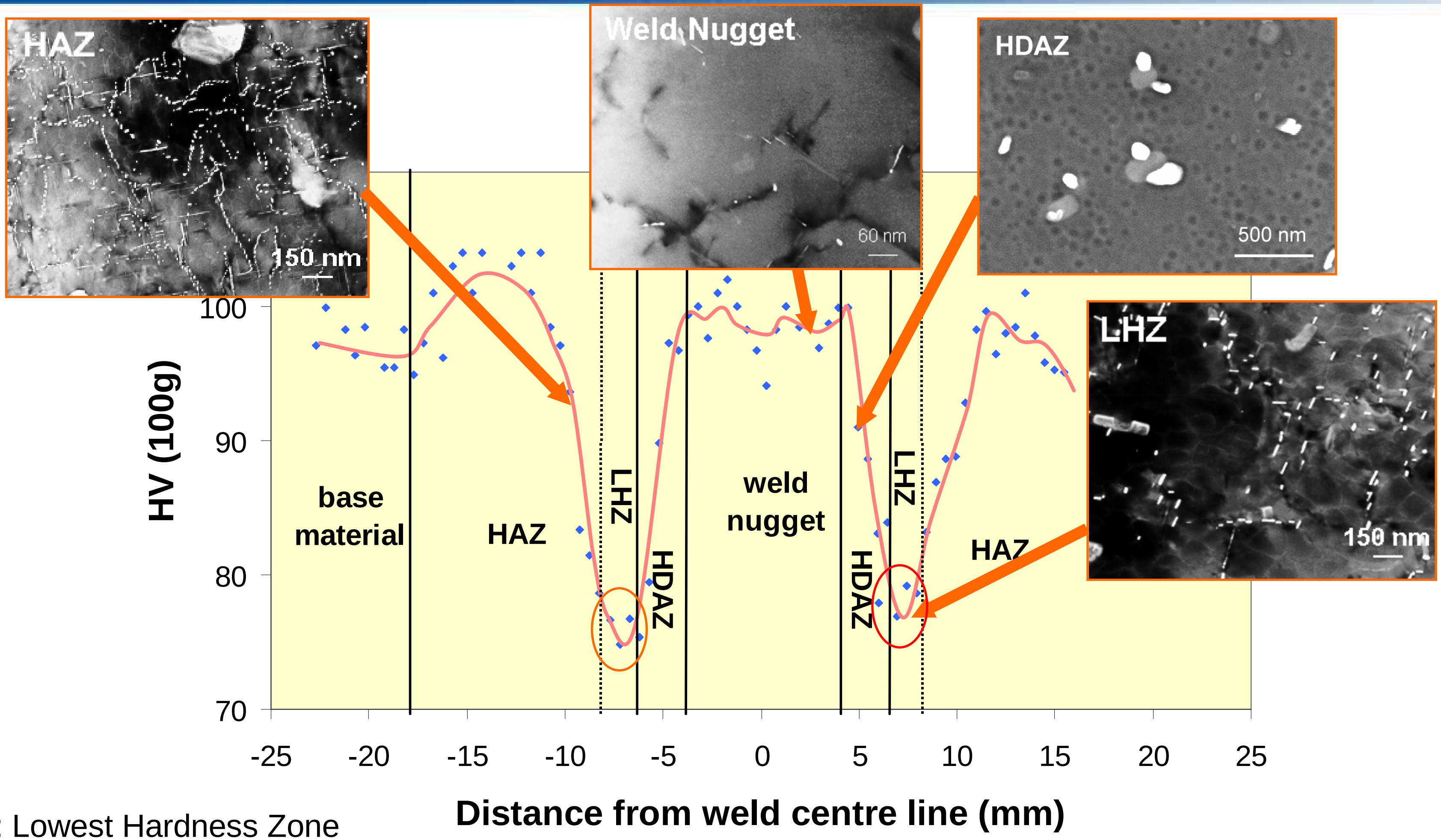


<u>Weak hardness zone</u> :
Coarse precipitation
Low supersaturation



(from Russell and Shercliff, 1rst Int. FSW Symp., Thousand Oaks (1999)

Heat treatable alloys : the case of naturally aged alloys

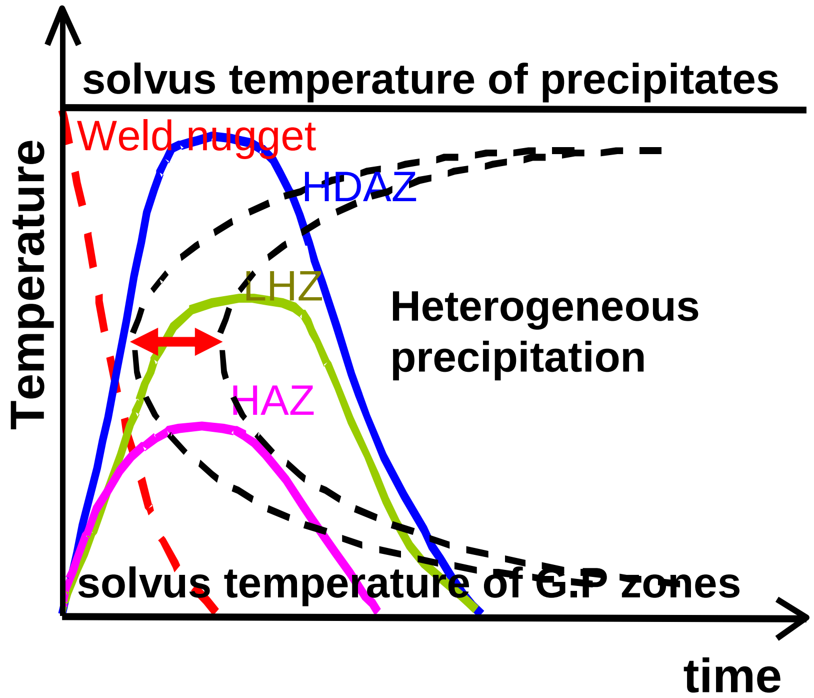


LHZ : Lowest Hardness Zone

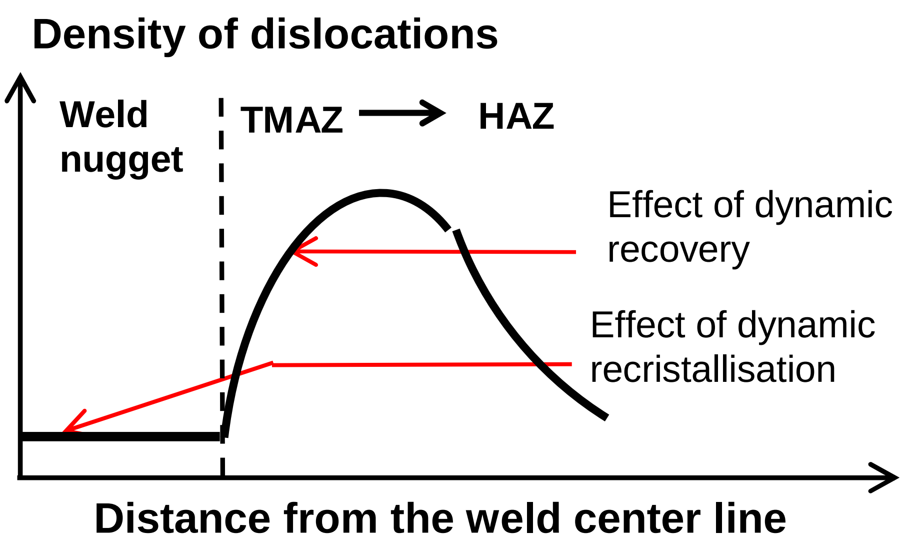
FSW of 6056-T4 : Weakest zone near the TMAZ/HAZ interface due to coarse and intense heterogeneous precipitation *(Denquin et al., Mater. Sci. Forum 3 (2002)).*

Heat treatable alloys : the case of naturally aged alloys

Effect of thermal cycle

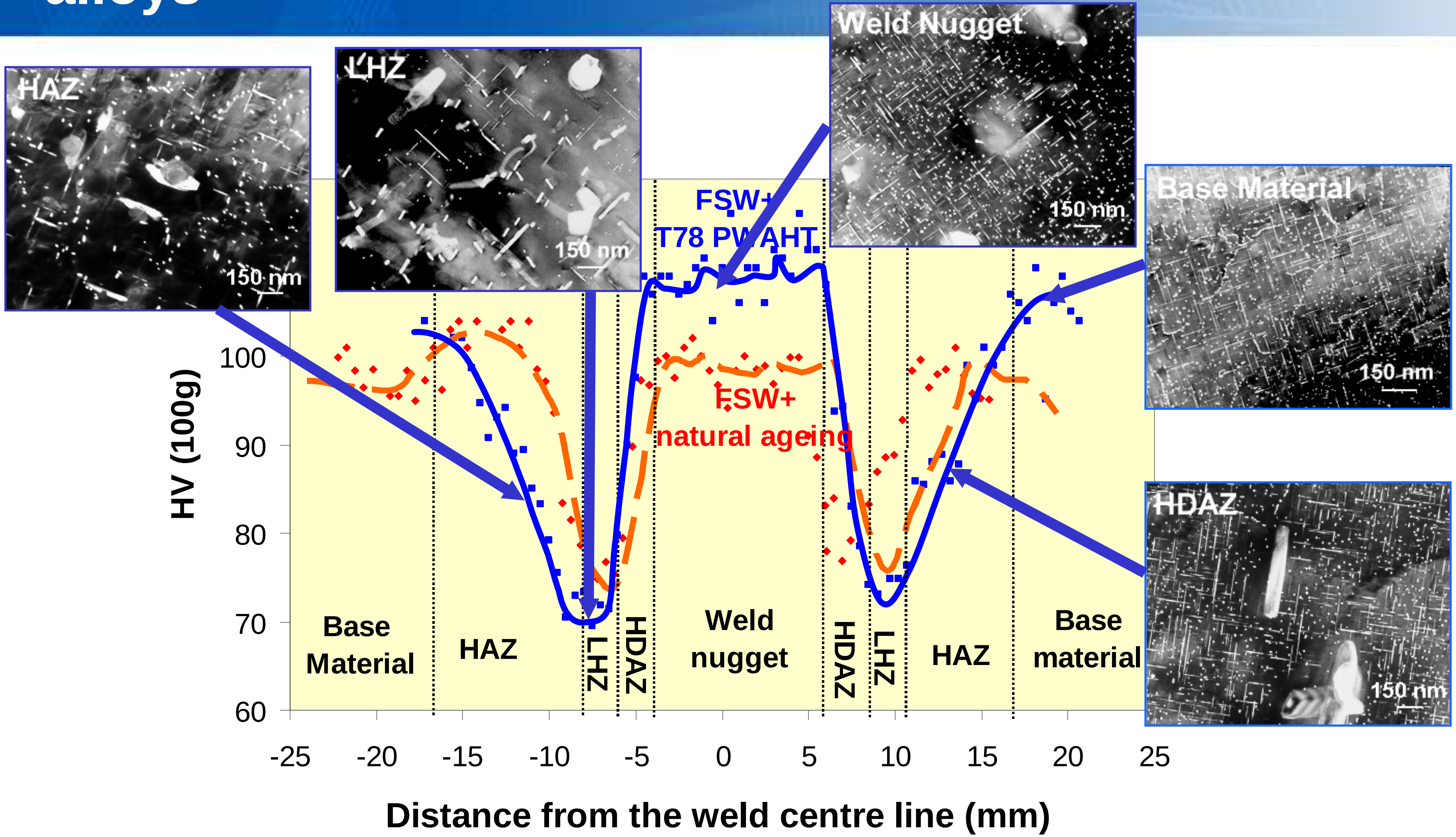


Effect of nucleation sites density



Coarse and intense heterogeneous precipitation in the Weak hardness zone (LHZ)
➔ no hardening potential left in this zone

Heat treatable alloys : the case of naturally aged alloys



Influence of a PWHT : no solid solution left in the weakest zone = no hardening
(Denquin et al., Mater. Sci. Forum 3 (2002)).

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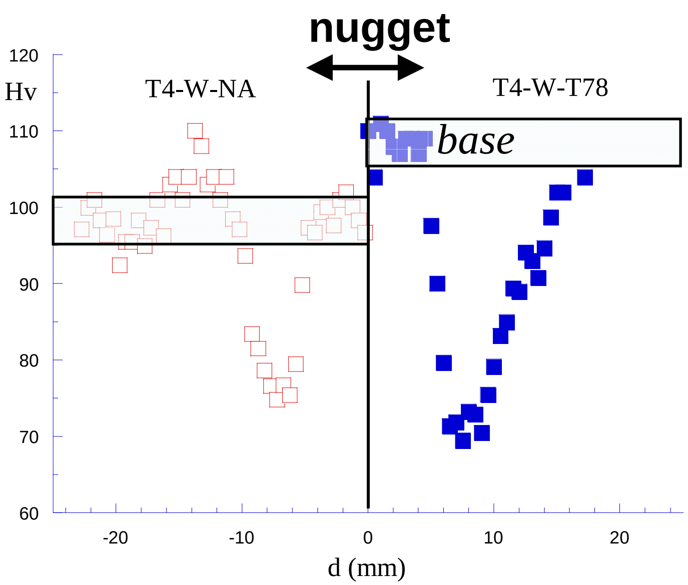
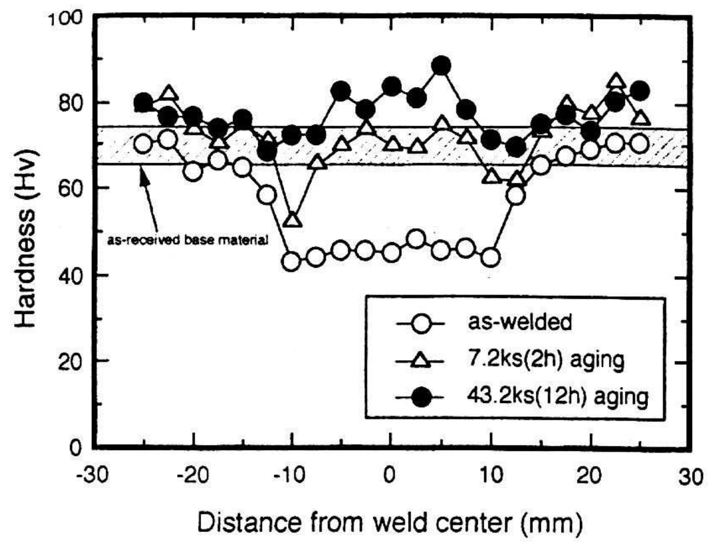
Heat treatable alloys : Influence of composition

Low trempability alloy



6056-T4 FSW alloy :
Influence of a post-weld heat treatment *((left : after natural ageing, right : after post-weld heat treatment)*

High trempability alloy



6063-T5 FSW alloy :
Influence of a post-weld heat treatment *(from Sato et al. Metall. Mater. Trans., 30A (1999), 3125)*

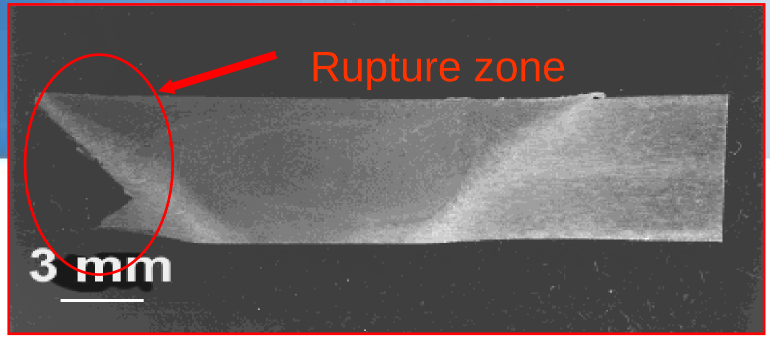
Tensile behaviour of FS welds

Friction stir weld joint efficiency for various aluminum alloys

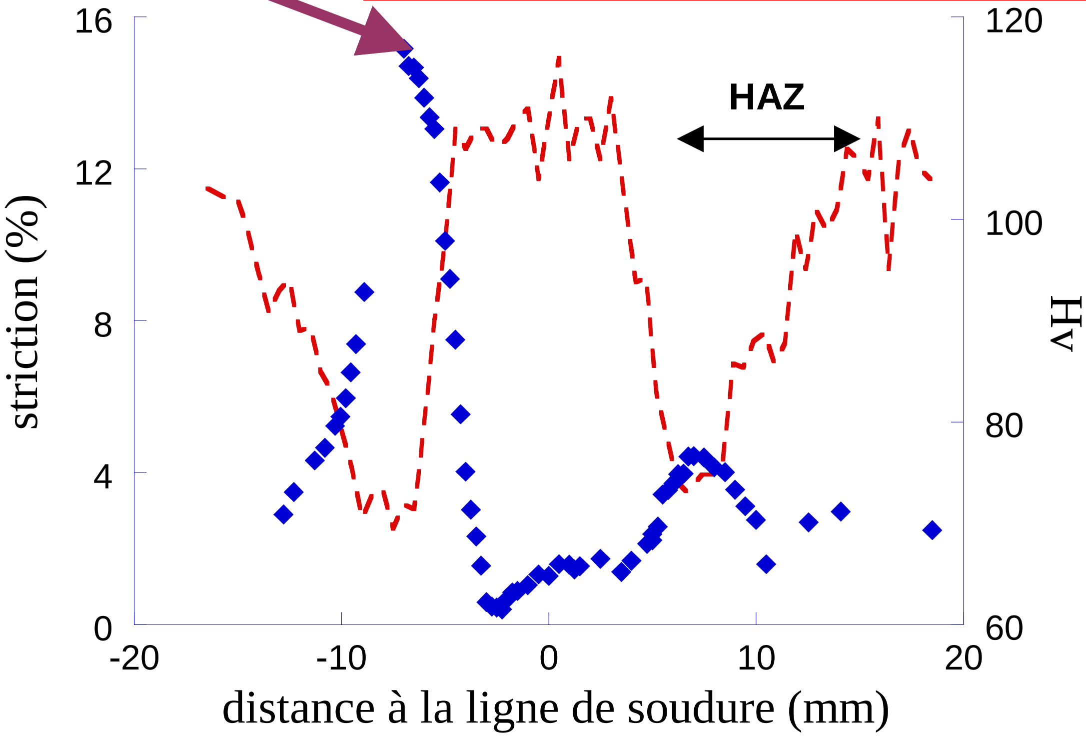
Alloy	Base metal UTS	Friction stir weld UTS	Joint efficiency (%)	References
AFC458-T8	544.7	362.0	66	[131]
2014-T651 (6 mm)	479–483	326–338	68–70	[131,134]
2024-T351 (5 mm)	483–493	410–434	83–90	[131,135]
2219-T87	475.8	310.3	65	[131]
2195-T8	593.0	406.8	69	[131]
5083-O (6–15 mm)	285–298	271–344	95–119	[12,131,132,134]
6061-T6 (5 mm)	319–324	217–252	67–79	[131,135]
7050-T7451 (6.4 mm)	545–558	427–441	77–81	[102,131,138]
7075-T7351	472.3	455.1	96	[131]
7075-T651 (6.4 mm)	622	468	75	[41]
6056-T78 (6 mm)	332	247	74	[133]
5005-H14 (3 mm)	158	118	75	[135]
7020-T6 (5 mm)	385	325	84	[135]
6063-T5 (4 mm)	216	155	72	[78]
2024-T3 (4 mm)	478	425–441	89–90	[136,137]
7475-T76		465	92	[136]
6013-T6 (4 mm)	394–398	295–322	75–81	[75,137]
6013-T4 (4 mm)	320	323	94	[75]
2519-T87 (25.4 mm)	480	379	79	[89]

(Mishra and Ma, Materials Science and Engineering R 50 (2005))

Tensile behaviour of FS welds



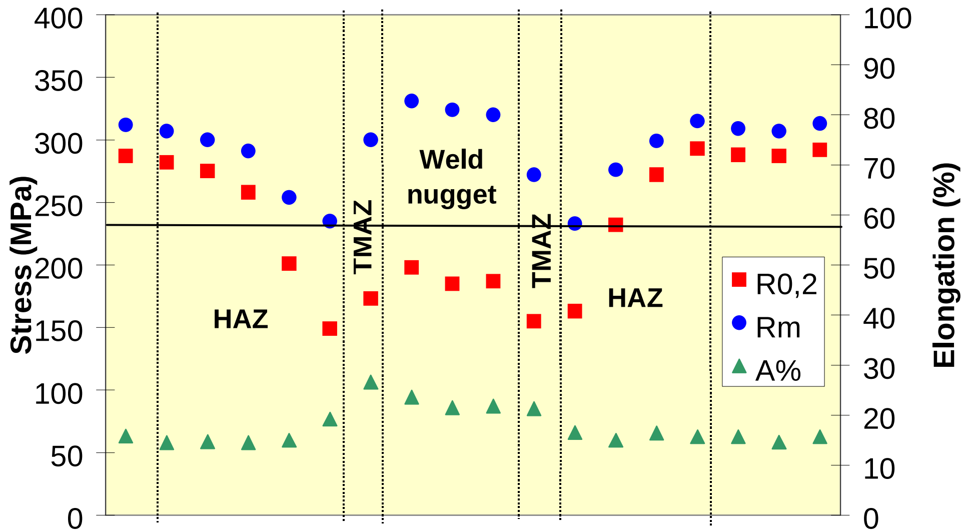
rupture



6056-T4 FSW +T78
Joint efficiency : 78%
Elongation to rupture : 2,2%

Similar behaviour reported for FS welds of **2024-T3** *(Biallas et al., MP Materialprüfung, 42 (2000) 6)* **and 7075-T6** *(Mahoney et al., Metall. Mater. Trans. A 29 (1998)).*

Local to global tensile properties



Results obtained from tensile micro-specimens extracted from the FS 6056-T78 weld (Denquin, et al., Welding in the world (2002))

0.2% weld plastic strength ≈ $(\sigma_{0.2})_{\text{weak zone}}$

Partitioning of plastic deformation ➔ ultimate properties of the weld

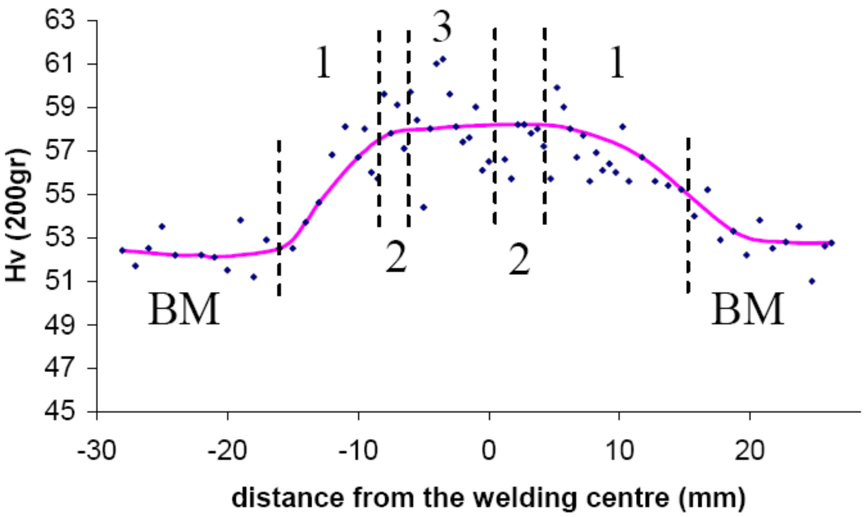
❖ $\sigma_{0.2} < (\sigma_m)_{\text{weak zone}}$ ➔ yielding of the weak zones, TMAZ and weld nugget

❖ strain hardening capability of the weak zones + stress triaxiality

➔ macroscopic elongation to rupture of the weld

➔ Preferential deformation of the weak zone until rupture

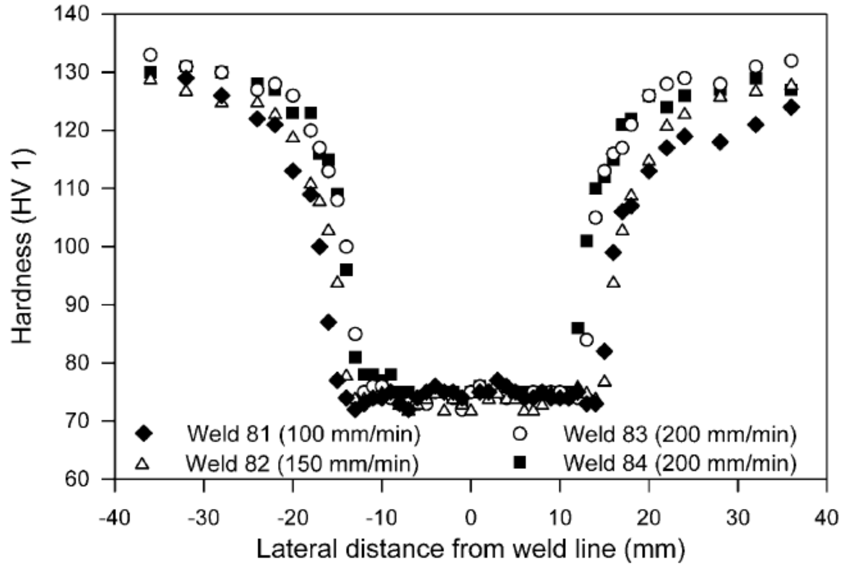
Non heat-treatable Al alloys



5251 O (solid solution hardened)

(from Genevois et al., 5th Int. FSW Symp., Metz, 2004)

1 : transition zone, 2 : TMAZ, 3 : Nugget



5083 H19 (work hardened)

(from Peel et al., Acta Materialia 51 (2003))

The overall behaviour is governed by the relative strengthening contributions from grain boundaries, particles and substructure.

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(Mishra and Ma, Materials Science and Engineering R 50 (2005))

Fracture toughness of FS welds

Material	Notched region	CTOD (mm), $\delta_{0.2BL}$ [a]	J (kJ/m^2), $J_{0.2BL}$ [a]
2014Al-T651	Base metal	0.011	6.6
	Center of weld nugget	0.060	22
	HAZ/TMAZ	0.065	27
	HAZ/TMAZ	0.049	20
	TMAZ 0.5 mm from the edge of weld nugget on advancing side	0.051	17
7075Al-RRA[b]	Base metal	0.012	9.5
	Center of weld nugget	0.024	12.7
	HAZ/TMAZ	0.082	30
	HAZ/TMAZ	0.084	31
	TMAZ 0.5 mm from the edge of weld nugget on advancing side	0.036	17.2
5083Al-O	Base metal	0.159	47
	Center of weld nugget	0.201	64
	HAZ/TMAZ	0.177	50
	HAZ/TMAZ	0.201	59

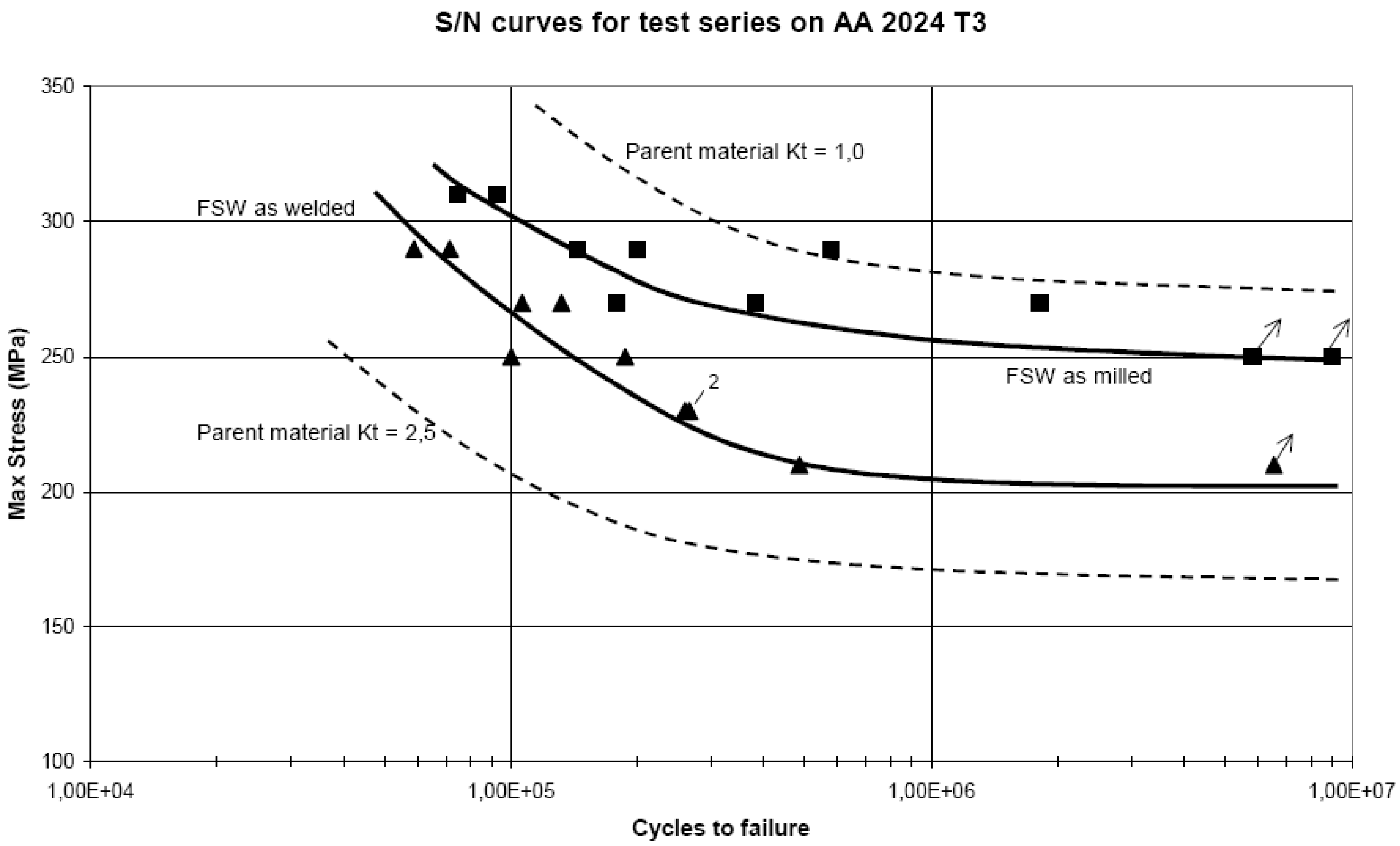
[a] $\delta_{0.2BL}$ and $J_{0.2BL}$ are very similar to the δ_{Ic} and J_{Ic} fracture toughness, respectively, in the ASTM E 1820-99 test method.
[b] RRA refers to retrogression and re-aging (rapid heating to 220 °C, kept for 5 min, cold water quenched, re-aged at 120 °C for 24 h).

(from Dawes et al., 2nd Int. FSW Symp., Göteborg, 2000)

FS welds present higher fracture toughness than the corresponding parent metals

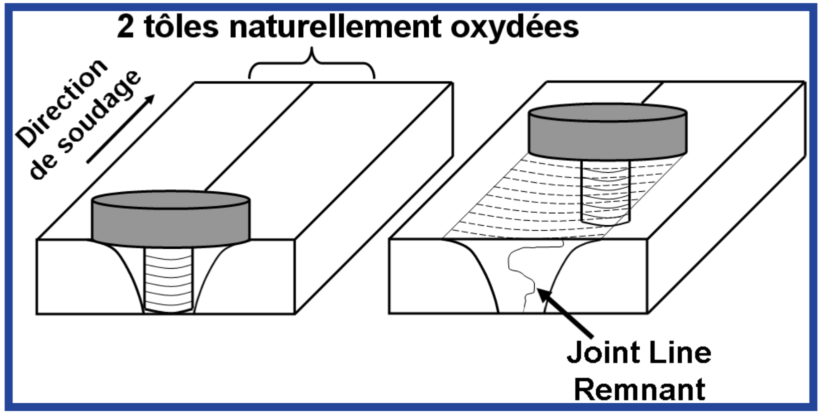
- **↗ by fine grain structure and small particles (nugget zone),**
- **↘ through low yield stress and high ratio of high-angle boundaries**
- **↘ PFZ and caoarsened particles (HAZ/TMAZ of some welds)**

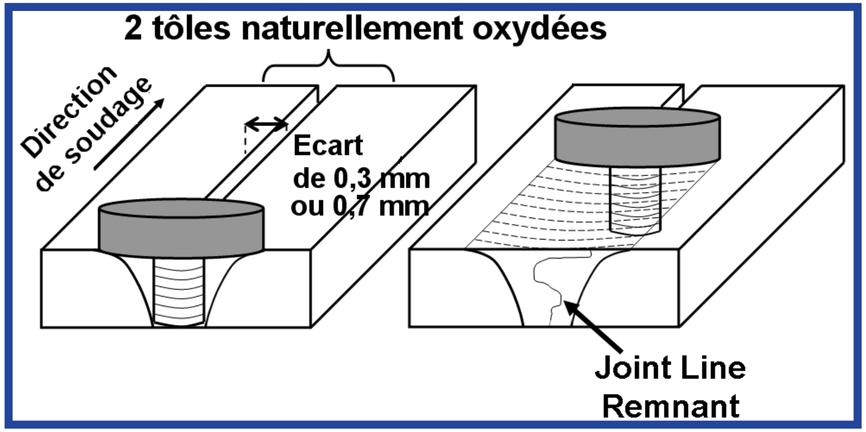
Fatigue properties of FS welds : S-N curves

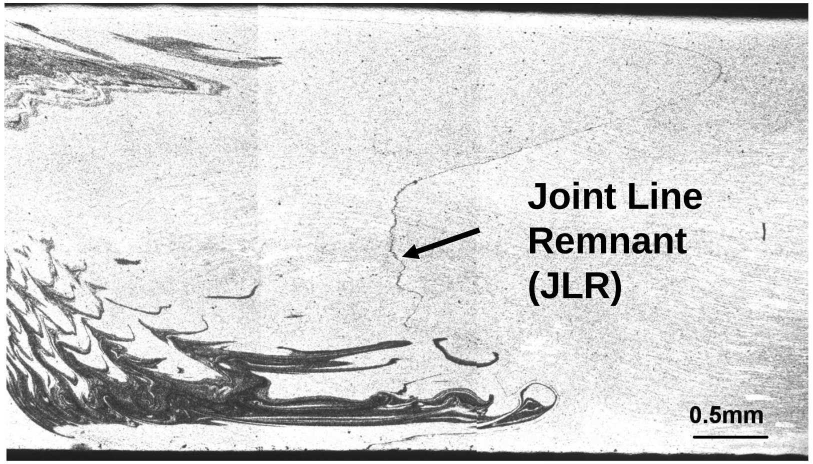


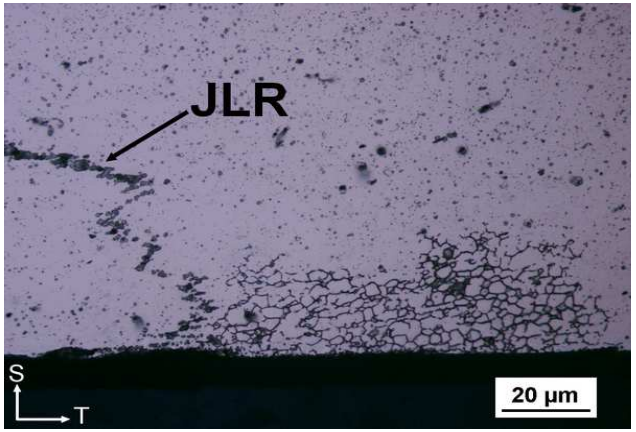
(From Magnusson et al.,2nd symp. on FSW, 2000)

Fatigue properties of FS welds : defects influence





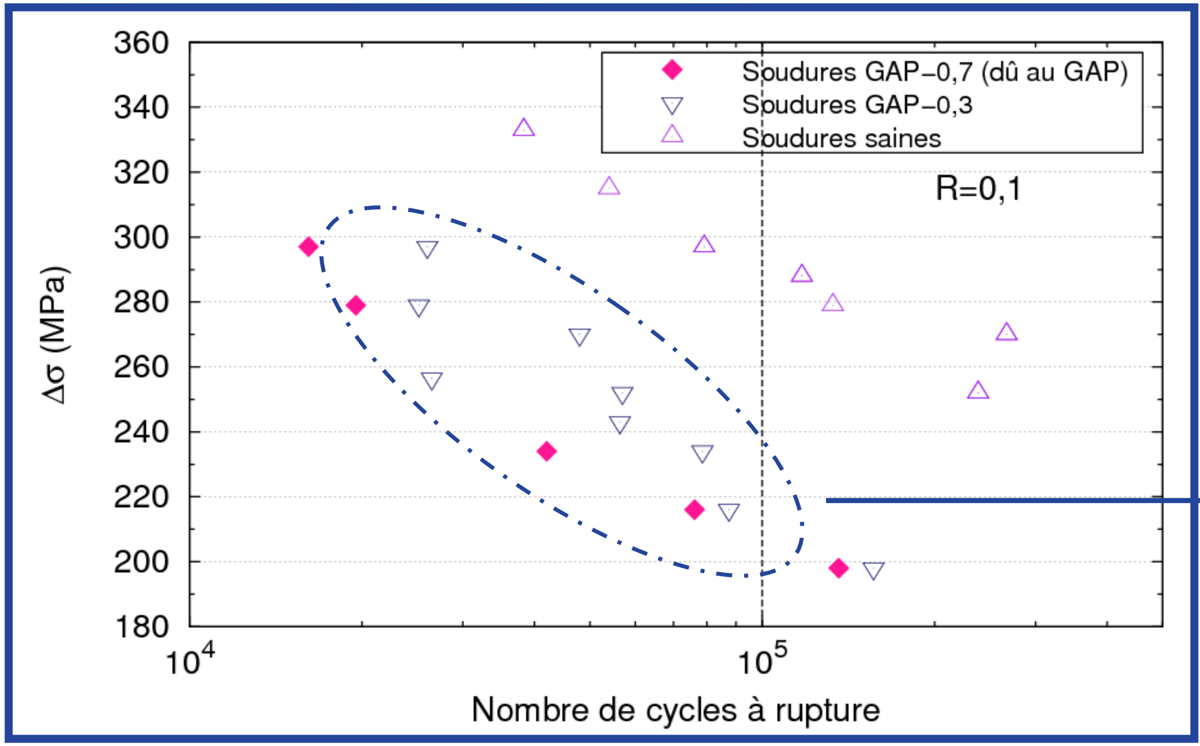


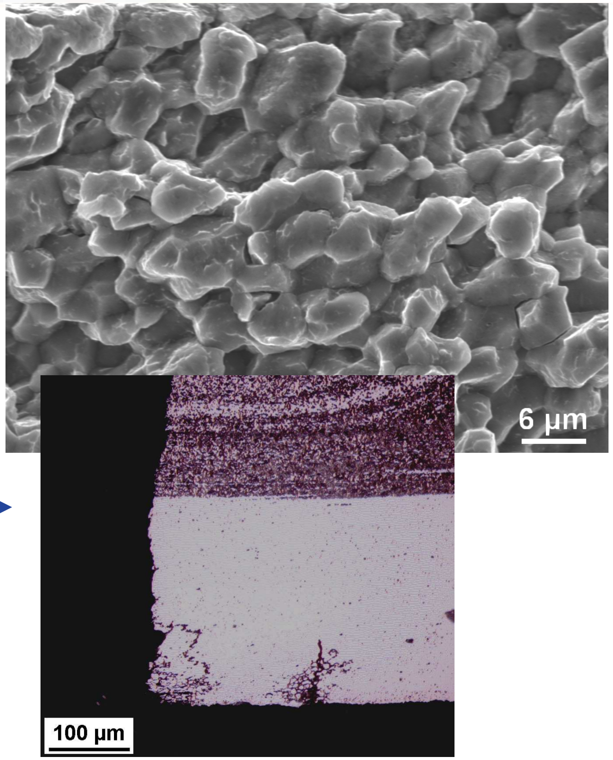


Cross section of 2198 FS welds after chemical and electrochemical etching to reveal oxide line and gap-type defect

(FRAE MASAE project, 2011)

Fatigue properties of FS welds : defects influence



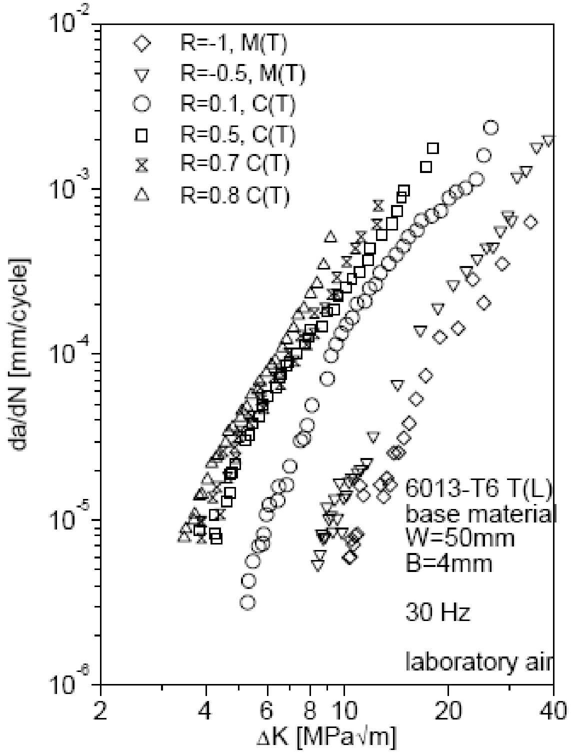


Defects detrimental to fatigue behavior result from material flow in the nugget because of bad positioning of coupons before welding

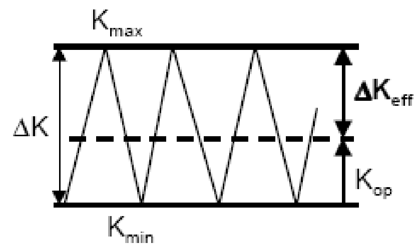
Careful attention must be paid to pre-welding operations

(From T. Le Jolu, PhD thesis, 2011)

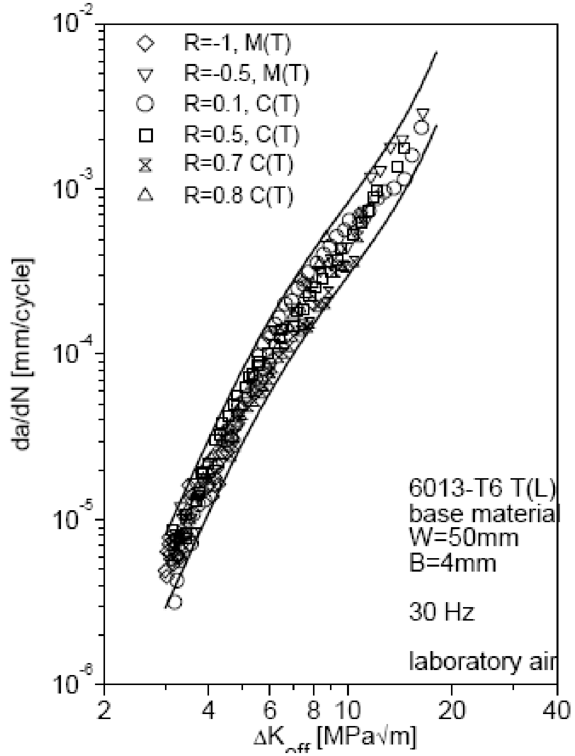
Fatigue behaviour of FS welds : fatigue crack propagation



$\Delta K_{eff} = K_{max} - K_{op} = f(K_{max}, R)$



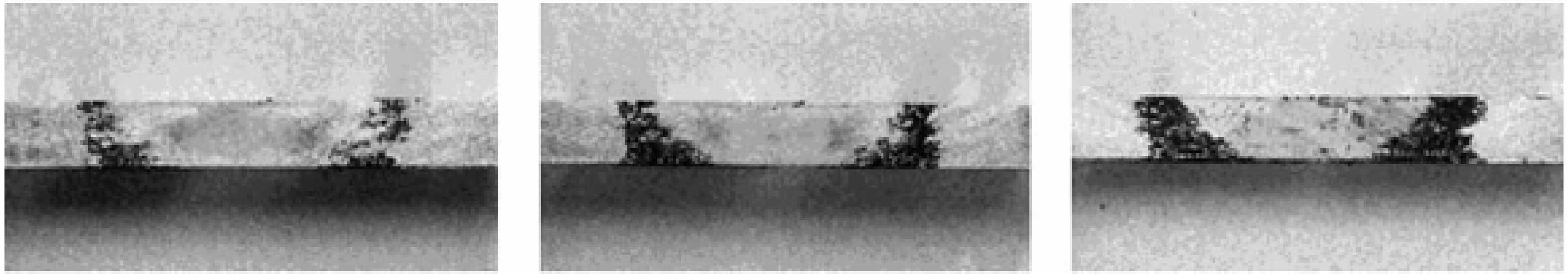
Taking into account compressive residual stresses at the crack tip region in the FSW welds through the effective stress intensity factor range ΔKeff



(from Dalle Donne et al., 2nd Int. FSW Symp., Göteborg, 2000).

Influence of residual stresses on fatigue crack propagation (similar behaviour obtained for 2024-T3 alloy),

Corrosion Properties of FS welds



Corrosion attack of FSW 7075Al-T651following extended exposure to a solution of 4 M NaCl–0.5M KHO3–0.1 M HNO3 diluted to 10%

(after Lumsden et al., Corrosion 55 (1999)).

Pitting potentials of FSW aluminum alloy welds in different locations (mV_{SCE})

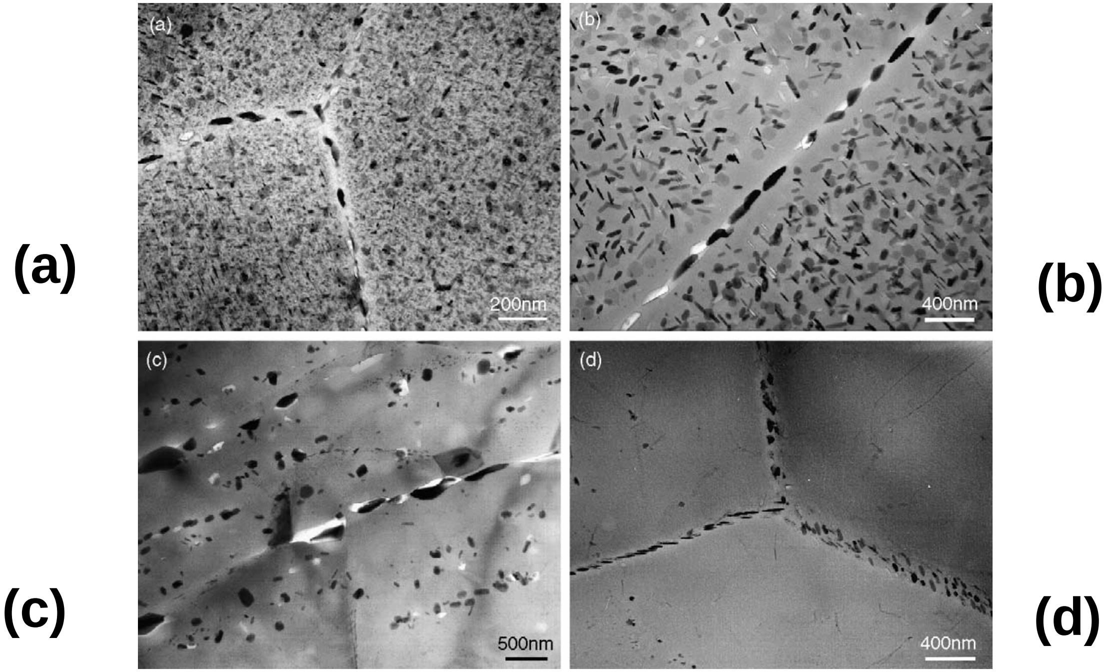
Material	Corrosion zone	Weld nugget	Base metal	Reference
7075Al-T651	−798	−772	−758, −713[a]	[75]
7010Al-T7651	−712	−704	−686	[159]
2024Al-T351	−638	−566	−540	[159]

[a] 7075Al base has two pitting potentials.

(From Mishra and Ma / Materials Science and Engineering R 50 (2005))

FS welds are susceptible to intergranular attack in the HAZ, TMAZ and in the weld nugget

Corrosion Properties of FS welds



Precipitate microstructures in the grain interior and along grain boundaries in a 7050 T6 FSW : (a) parent material, (b) HAZ, (c) TMAZ I, (d) TMAZ II,

(from Su et al., Acta Mater. 51 (2003))

Large influence of microstructural evolution on corrosion behavior of FS welds

How to optimise friction stir welds ?

- Precipitation evolution resulting from the thermal and mechanical cycles during FS processing plays a major role on :
  - Static properties (structural behaviour, forming operations)
  - Corrosion resistance

    ➔ Optimization through process parameters (but staying inside the process windows)

    ➔ Optimisation through post weld thermal or thermo-mechanical treatment (hardening heat treatment possible but may be detrimental to elongation of the weld, stretching may favour hardening precipitation…)

- Fatigue properties are governed by :
  - Residual stresses (may be detrimental for thick products)
  - Weld asperities or defects (such as shoulder trace, root flaw or GAP-type defect)

    ➔ Optimisation through process parameters, pre or post welding operation

How to optimise friction stir welds ?

- ❖ Further work needed :
  - ➢ To clarify influence of various microstructural zones on :
    - Fracture thoughness
    - Corrosion behaviour
  - ➢ To understand defect formation in the nugget, in relation with material flow

- ❖ Optimising behavior of structural panels :
  - ➢ Modeling the influence of FSW process on in-service joint performance : coupling thermal, microstructural, strength and strain hardening models

    Cf PhD of C. Gallais, Aude Simar (Progress in Matrials Science, 2012)
  - ➢ Welding of dissimilar aluminium alloys