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CASE STUDYS OF LASER WELDING AND WELDABILITY

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Outline

- Case 1:
  - Laser welding and weldability of hard D2 tool steel
- Case 2:
  - Laser welding of EN AW 6060 with die casted part of AlSi10
- Case 3:
  - Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube

- Other topics of interest (we would like to establish collaboration)
  - Laser welding of Cu and Al (currently green lasers are interesting due to higher absorption of laser light)
  - Laser color engraving
  - Laser active flux welding
  - Laser welding of advanced high strength steels for automotive applications
  - Additive manufacturing

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Case 1: Welding and weldability of hard cold work tool steel AISI D2 – material data

Area of interest: repair welding of damaged industrial tools (cutting tools, forming dies, …

Steel OCR12VM (Mat.No. 1.2379, DIN X155CrVMo12-1, AISI D2)

Designation by Standards

Brand Name	Ravne No.	Mat. No.	DIN	EN	AISI
OCR12	834	1.2379	X155CrVMo12-1	X160CrMoV121	D2

Chemical Composition (in weight %)

C	Si	Mn	Cr	Mo	Ni	V	W	Others
1.53	0.35	0.40	12.00	1.0	-	0.85	-	-

- **Description:** high C and Cr type tool steel, deep hardened, high wear resistance. Air hardened with low distortion after cooling.
- **Applications** where wear resistance is important, blanking or forming dies and threaded rolling dies, cutting tools, stamping, woodworking, molding tools for plastics, …

Physical properties (avarage values) at ambient temperature

Modulus of elasticity [10^3 x N/mm^2]: 210

Density [g/cm^3]: 7.70

Thermal conductivity [W/m.K]: 20.0

Electric resistivity [Ohm mm^2/m]: 0.65

Specific heat capacity[J/g.K]: 0.46

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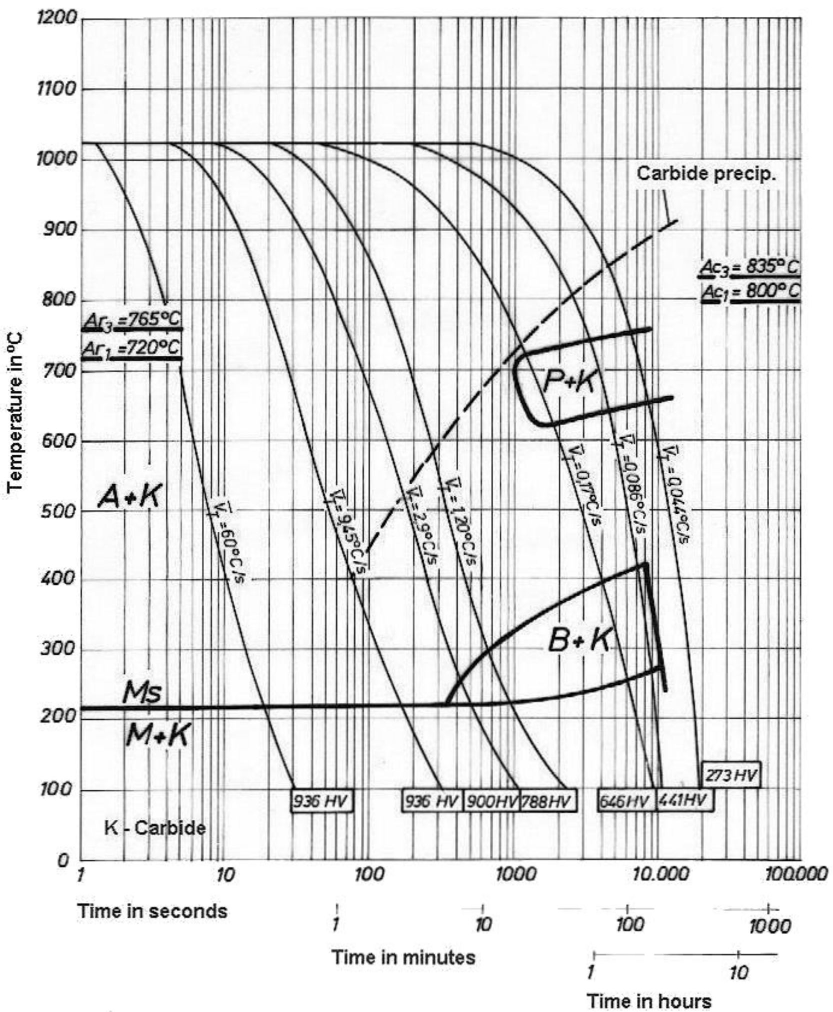
Case 1: Welding and weldability of AISI D2 steel – heat treatment

CCT Diagram



Soft Annealing

Heat to 840-880°C, cool slowly. This will produce a maximum Brinell hardness of 255. To secure uniform softness.

Stress Relieving

Stress relieving to remove machining stresses should be carried out by heating to 650-700°C, holding for one hour at heat, followed by air cooling. This operation is performed to reduce distortion during heat treatment.

Hardening

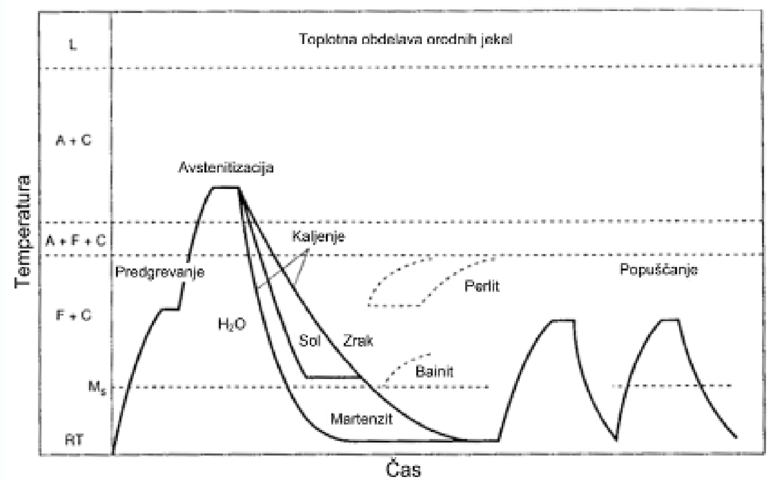
Harden from a temperature of 1000-1040°C followed by oil, warm bath (500-550°C, cooling bath or air. Hardness after quenching is 62-64 HRC.

Tempering

Tempering temperature: 150-550°C.

Tempering Temperature (°C) vs. Hardness (HRC)

100°C	200°C	300°C	400°C	500°C	525°C	550°C	600°C	700°C
63	61	58	58	59	58	56	51	35



Tempering temperature [°C], 1.5h

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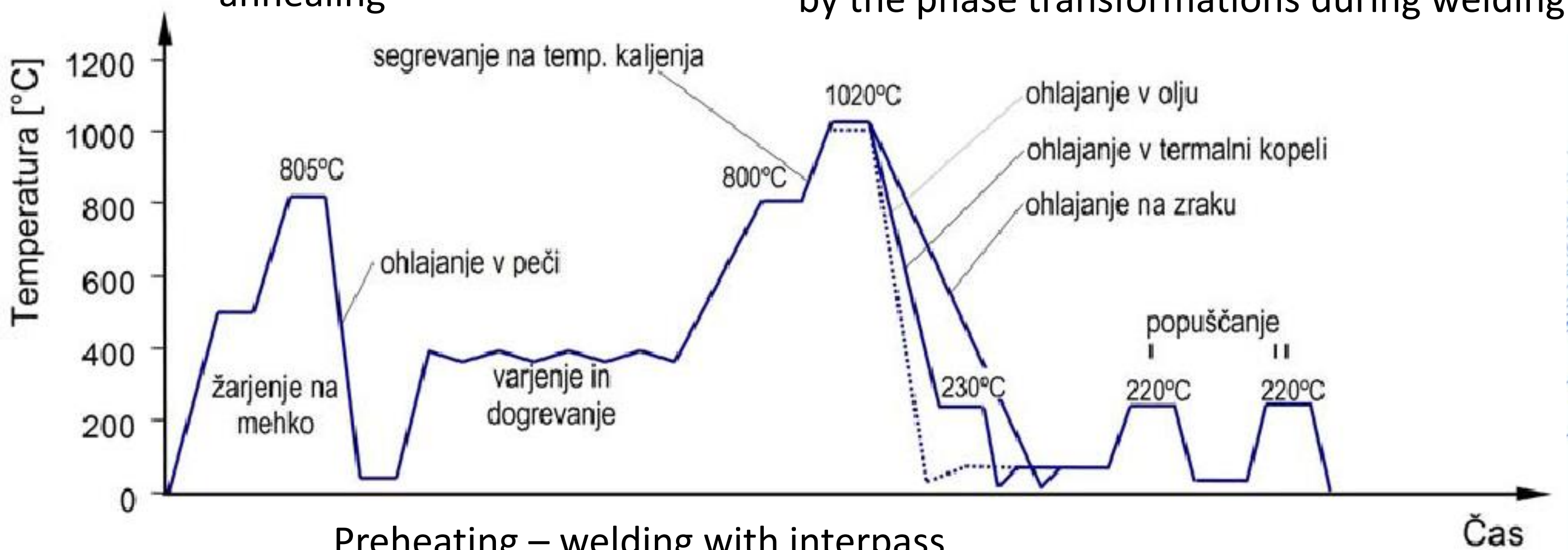
Case 1: Welding and weldability of AISI D2 steel – welding

- A massive amount of alloying elements makes D2 steel very difficult to weld → cracking. Carbides are usually responsible for crack initiation and the critical stress for crack initiation is lowered with the carbides being bigger.
- A tungsten inert gas (TIG) welding is usually used for welding in soft annealed condition with preheating.

Soft annealing

post weld heat treatment (PWHT) → to avoid solidification cracking and residual stresses induced by the phase transformations during welding



Preheating – welding with interpass temperature (370 – 480 °C)

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Case 1: Welding and weldability of AISI D2 steel – experimental laser welding

A pulsed 200 W laser (Lasag Easy welder SLS CL 60)
a Castolin filler wire with 0.35 mm diameter.
An Argon 5.0 with a flow of 6 l/min was used as a shielding gas.

Table 1 Chemical compositions of base and filler material

Material	Chemical composition [wt - %] (OES analysis)								
	C	Si	Mn	Cr	Mo	Ni	V	W	Fe
AISI D2	1,53	0,35	0,40	12	1,0	-	0,85	-	bal.
filler wire	0,73	1,8	0,22	9,2	0,26	0,1	0,28	0,1	bal.

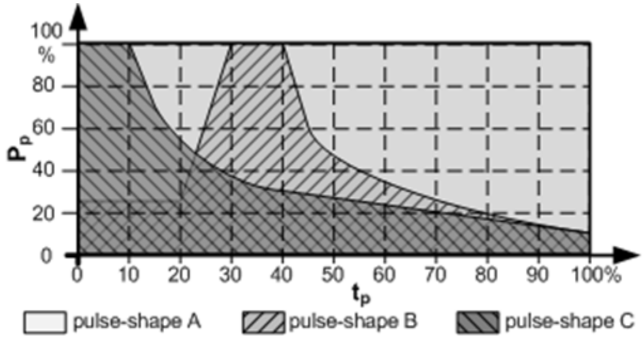

Figure 1. Applied laser pulse shapes

Table 2 Laser parameters for the applied laser pulse shapes

Pulse shape	Laser parameters *					
	f_l [mm]	P_p [kW]	t_p [ms]	E_p [J]	ν [Hz]	v [cm min^{-1}]
A	160	1,0	10	10,3	12	22
B	160	1,0	35	14,2	12	22
C	160	1,0	60	21,5	8	14

*f_l - focal length, P_p - pulse peak power, t_p - pulse duration, E_p - pulse energy, ν ⎕- repetition rate, v

Case 1: Welding and weldability of AISI D2 steel – laser remelting of base metal

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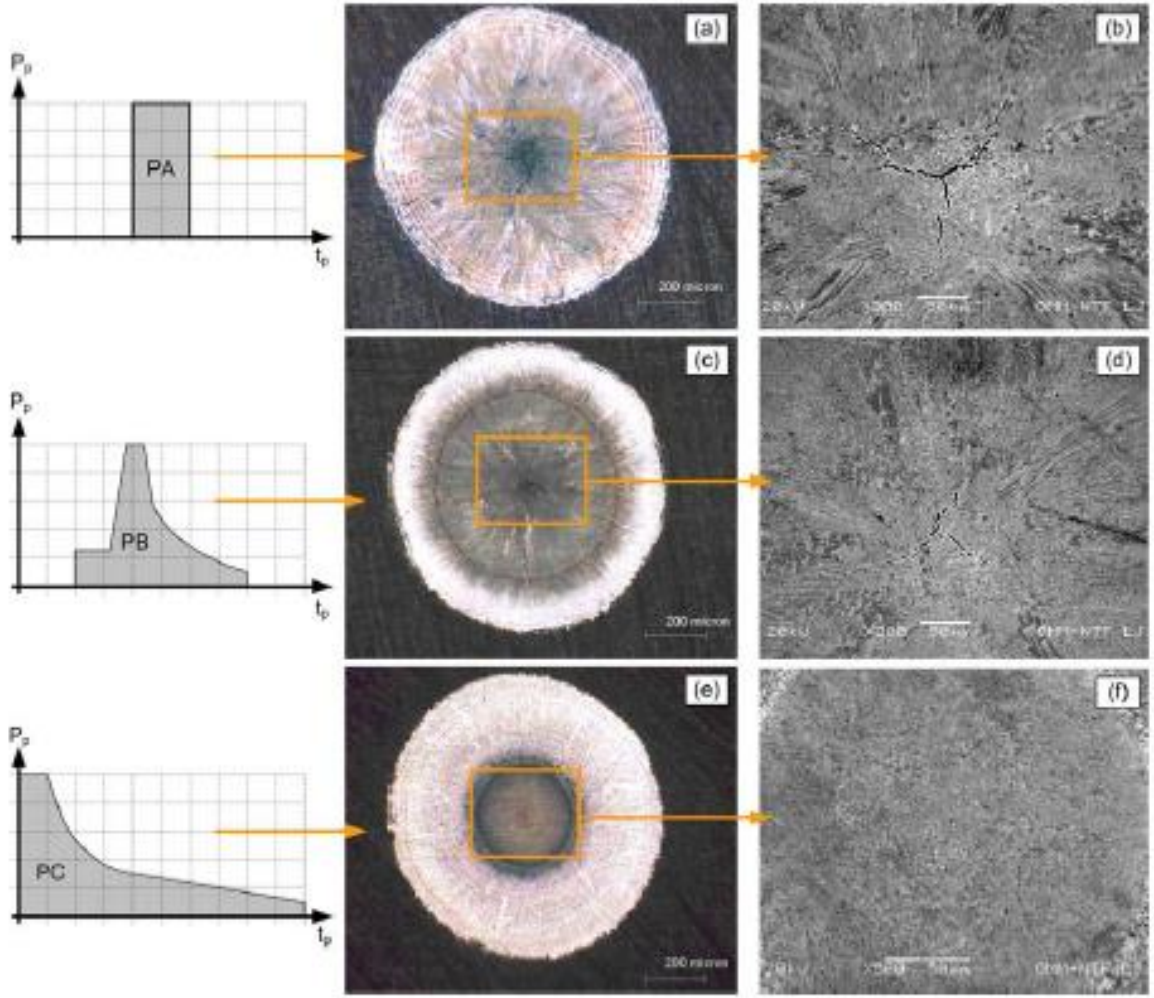

The use of laser pulse shape C – solidification cracking is omitted

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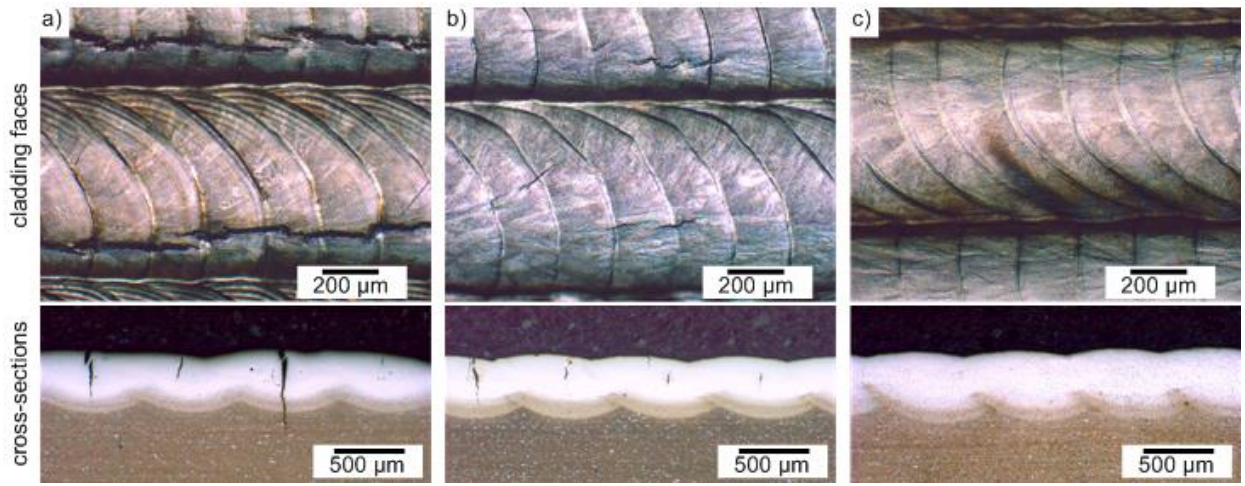
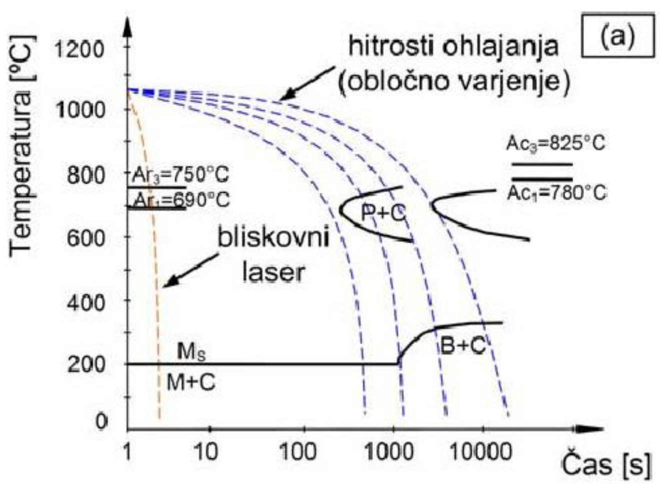
Case 1: Welding and weldability of AISI D2 steel – laser weld cladding

Macrographs of single layer claddings, presenting solidification cracking



A pulse, B pulse, flawless cladding made with pulse C.



- Laser cladding by wire due to localized heating effect reduces distortions and cracking during welding and allows the repair without any heat treatment → crack free layers with perfect bonding and a low degree of dilution.

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Case 2: Laser welding of EN AW 6060 with die casted part of AlSi10 – challenge description

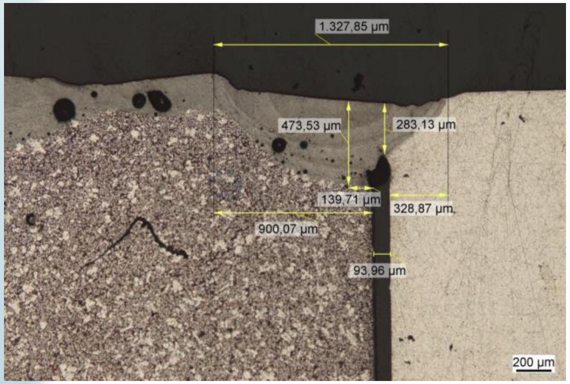
Area of interest: industrial challenge – heat exchanger for battery system

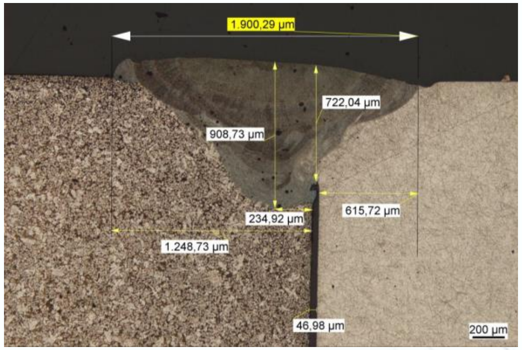
Status at the beginning

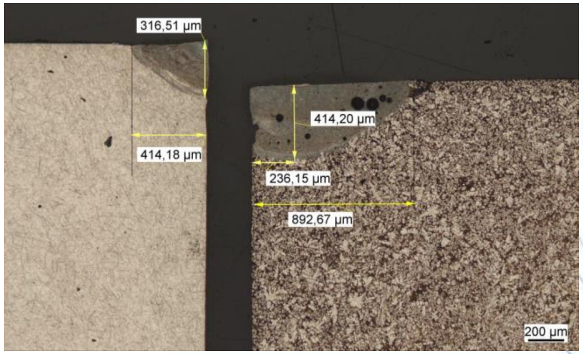
Heat exchanger (capable to carry 0.3 bar of pressure, testing pressure higher 3 bars and 15 bars, leakage must be avoided).

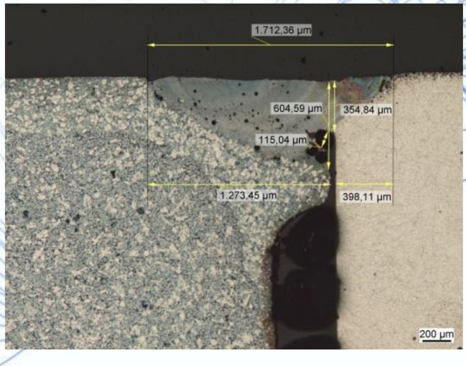
Robotic laser welding was used (problems with the positioning of laser beam)

~ 60 % of good pieces was produced (30 – 90 %), due to the problems → goal was to reach 95 % of good pieces.









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Case 2: Laser welding of EN AW 6060 with die casted part of AlSi10 – AC 43400 Al Si 10 Mg (Fe)

EN AW-6060 is a extrusion alloy. **Application:** furniture, finishing materials, windows and doors, carbody finishing, façade construction, lighting columns and flagpoles, architecture, and food industry.

Chemical composition according to EN573-3 (weight%, remainder Al)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	remarks	others each	others total
0.30 – 0.6	0.10 - 0.30	max. 0.10	max. 0.10	0.35 – 0.6	max 0.05	max 0.15	max 0.10		max 0.05	max 0.15

Mechanical properties according to EN755-2

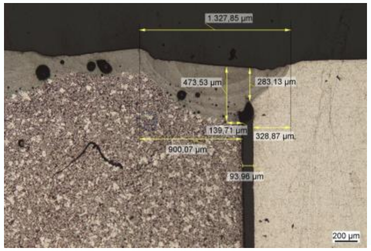
Temper*	Wallthickness e***	Yield stress $Rp_{0.2}$ [MPa]	Tensile strength Rm [MPa]	Elongation A [%]	Elongation A_{50mm} [%]	Hardness** HB
T4	e ≤ 25	60	120	16	14	45
T5	e ≤ 5	120	160	8	6	55
	5 < e ≤ 25	100	140	8	6	50
T6	e ≤ 3	150	190	8	6	65
	3 < e ≤ 25	140	170	8	6	60
T66	e ≤ 3	160	215	8	6	70
	3 < e ≤ 25	150	195	8	6	65

Physical properties (approximate values, 20 °C)

Density [kg/m³]	Melting range [°C]	Electrical conductivity [MS/m]	Thermal conductivity [W/m.K]	Co-efficient of thermal expansion 10^{-6}/K	Modulus of elasticity [GPa]
2700	585-650	28-34	200-220	23.4	~70

Weldability

Gas: 3 TIG: 2 MIG: 2, FSW, Ultrasonic, Laser, Electron Beam, …



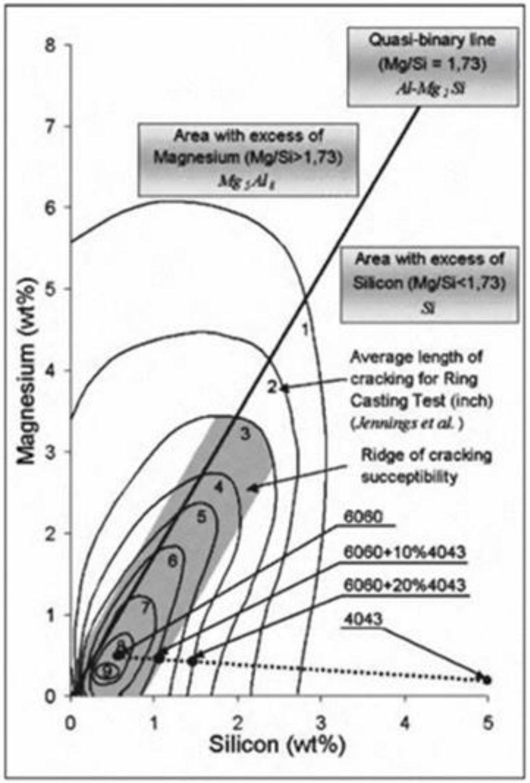


Figure 2 – Quasi-binary line superimposed on ring casting data of Jennings, *et al.* [5] showing solidification cracking susceptibility for Al-Mg-Si ternary alloy system

Al-Mg-Si alloys are known to be highly susceptible to solidification cracking except when using an appropriate filler metal *(typical filler materials (EN ISO18273): AlMg5Cr(A) or AlSi5, and AlMg3 when the product has to be anodised)* although the amount of dilution required to avoid cracking has never been a well-defined quantity. Due to the heat input during welding the mechanical properties will be reduced by approximately 50% (ref. EN1999-1).

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Case 2: Laser welding of EN AW 6060 with die casted part of AlSi10 – AC 43400 Al Si 10 Mg (Fe)

Aluminum + 10% Si,< 1% Fe, < 0.55% Mg …

Casting characteristics[2]:

Solidification range, ℃, about	Casting temperature ℃, about	Fluidity	Resistance to hot tearing	Shrinkage %, about	Pressure tightness
600-550	650-700	Excellent	Excellent	0,5-0,8	Good

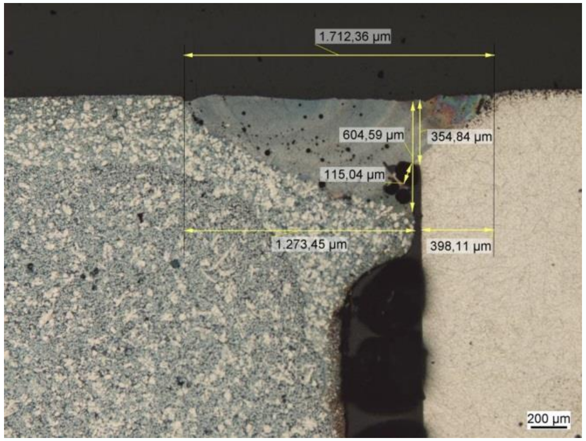
Mechanical properties of separately untreated cast test bars[2]:

Tensile strength, R_m, MPa, min.	Proof stress $R_{p0,2}$, MPa, min.	Elongation A_{50}, %, min.	Brinell hardness HBS, min.
240	140	1	70

Mechanical and physical properties[2]:

Density kg/dm³	Strength	Machinability	Weldability	Resistance to corrosion
2,65	Good	Good	Poor	Satisfact.

Decorative anodizing	Ability to be polished	Linear thermal expansion 293-373°K, °K⁻¹	Electrical conductivity MS/m	Thermal conductivity W/m°K
Not recom.	Poor	21×10^{-6}	16 – 21	130 - 150



Welding die cast products is possible if proper technique and measures are taken (hot cracks, gas bubbles, lubricants).

Rapid die filling causes the pore formation (*gas bubbles in pores are caused by a change in hydrogen solubility as the molten mass solidifies. The risk of air or nitrogen pores resulting from gases swept within the mass (if the dies are filled quickly), traces of lubricants on the castings*→ limited weldability.

Special welding technology is needed to encourage **degasification** and minimize the **undesired formation of inhomogeneous pores in the joint area**.

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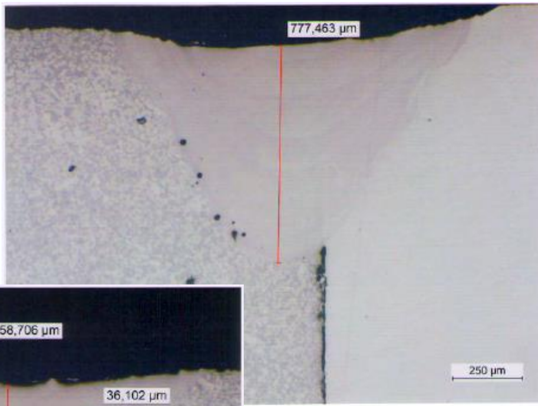
Case 2: Laser welding of EN AW 6060 with die casted part of AlSi10 – AC 43400 Al Si 10 Mg (Fe)

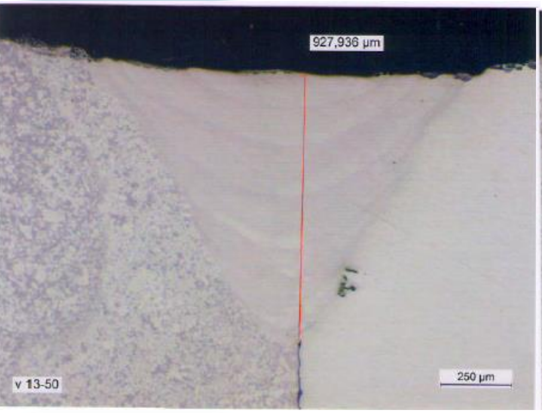
The problem was solved <u>by development of proper pulse shape and welding parameters</u> →
3 stage pulse shape was selected:

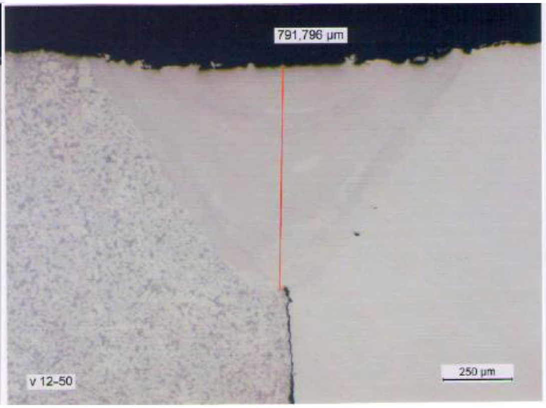
1 – welding,
2 – degasification,
3 – controlled cooling to prevent cracking in the AW 6060.

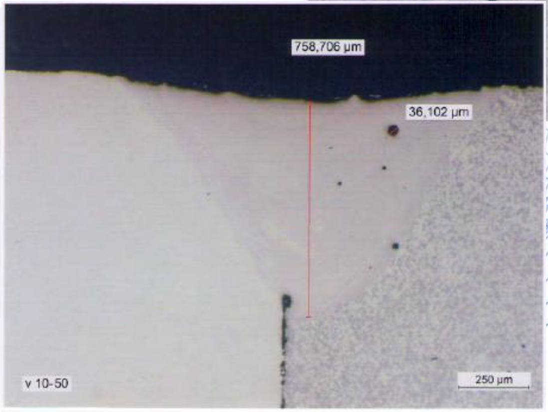
Laser limitation:

- Lack of function for welding aluminum (to remove surface oxidation layer)
- unflexible software for adjusting the laser pulse shape (only 6 points could be changed) → the proper welding parameters were crucial









Case 3: Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube

Goal: solve the weldability issue of Al_2O_3 surface coated on heating coil to tube.

The heating coil life could be prolonged if high temperature oxidation would be slowed down, by a compact Al_2O_3 surface coating.

- tube **Inconel 601**
- heating coil **Kanthal AF with Al_2O_3 surface coating (1 - 2 µm)**

- Chemical composition of the alloys in mass fractions

	Ni	Cr	Fe	Al	C	Si	Ti	Mn	Y	Zr
Inconel 601	60,2	22,9	13,9	1,33	0,04	0,21	0,43	0,59		
Kanthal AF	0,27	22,0	61,9	5,3	0,03	0,17	0,06	0,18	0,02	0,07

Case 3: Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube

		Inconel 601	Kantal AF	Al2O3
Coef. of thermal expansion 20-1000 °C	10^{-6} K^{-1}	10	15	8.4
Thermal conductivity at 50 °C	W/mK	11.3	11/27 (1200 °C)	35
Specific heat	J/Kg K	448	460-740	880
Melting point	°C	1360-1411	1500	2072

Background:

- Aluminum oxide layer of such thickness cannot be removed from the coil windings prior welding not during welding using AC welding current (small welding times).
- The difference in melting point and specific heat makes the Al2O3 difficult to re-melt during conventional arc welding.

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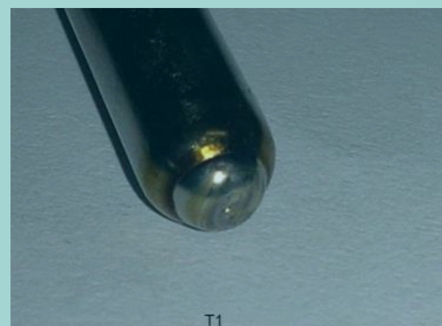
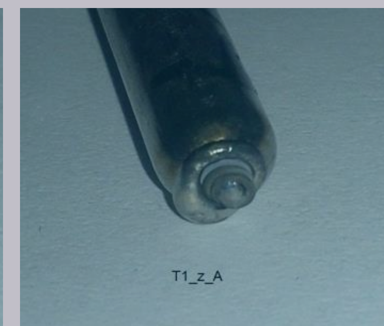
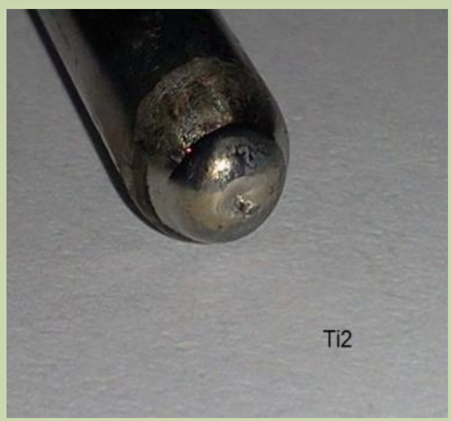
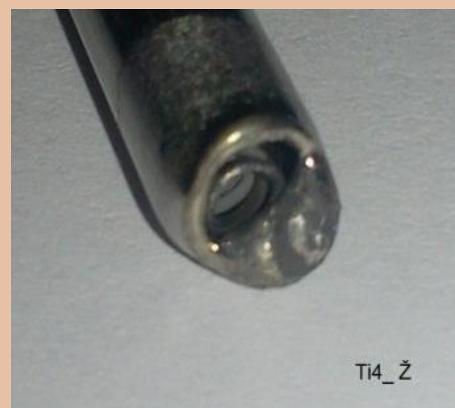
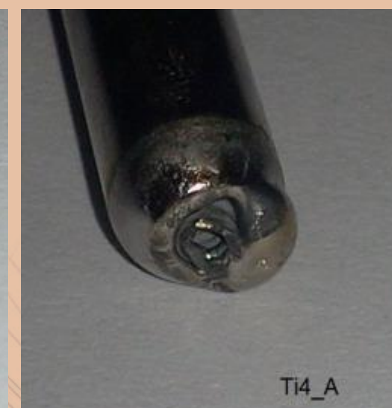
Case 3: Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube

TIG welding was unsuccessful

TIG welding

	Kanthal AF	Kanthal AF with Al_2O_3 surface coating (1 - 2 µm)	
DC (=) current			
AC (~) current			

TIG welding was done with small variation of welding parameters around: Iv = 55 A, tv = 0,10 s, If = 5 A, tf = 0,20 s, argon 4.8 shielding gas flow was 8 l/min.

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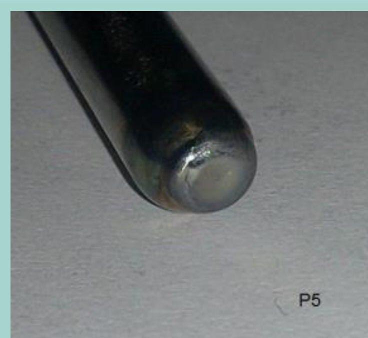
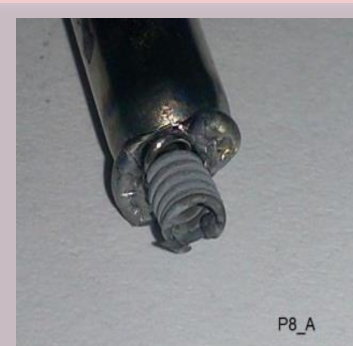
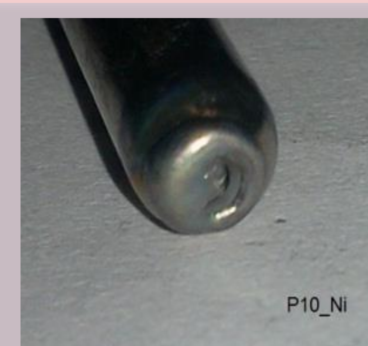
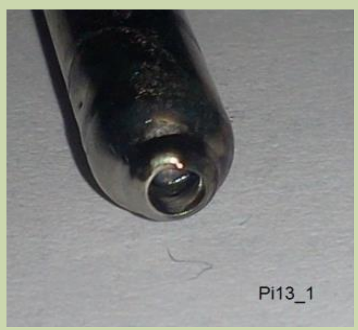
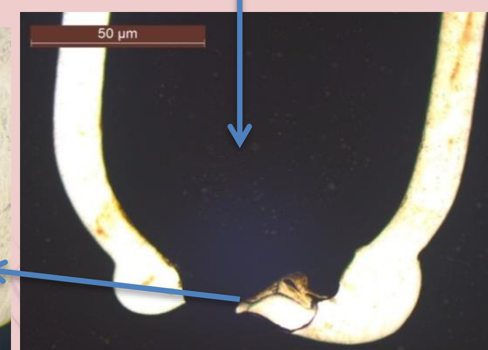
Case 3: Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube

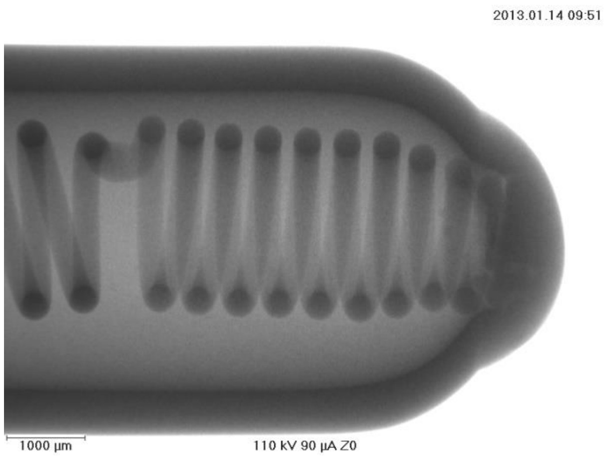
Plasma welding was unsuccessful

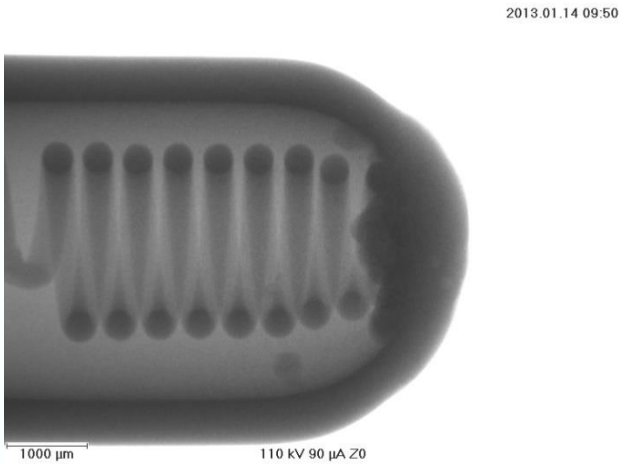
Plasma welding

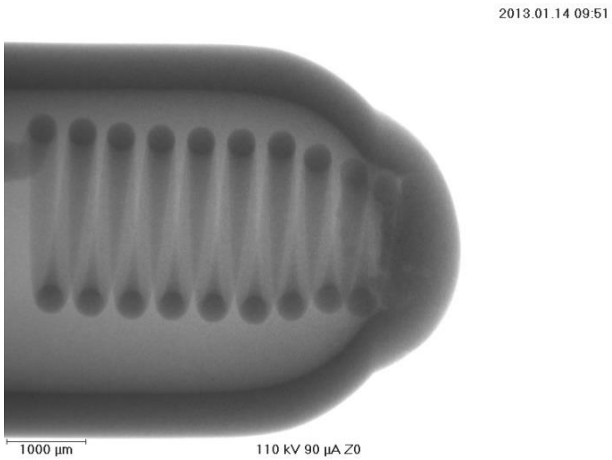
	Kanthal AF	Kanthal AF with Al_2O_3 surface coating (1 - 2 µm)	
DC (=) current			
AC (~) current			

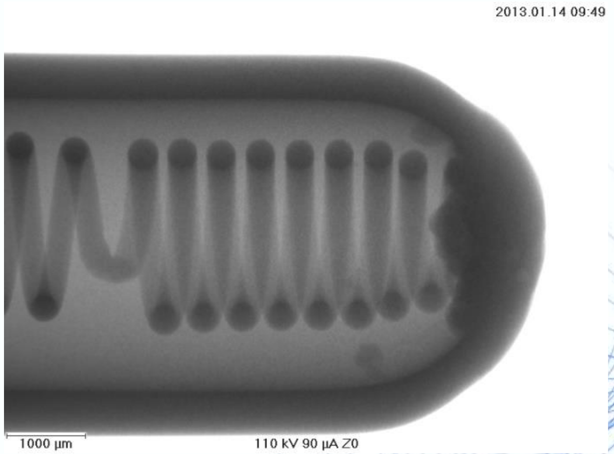
Plasma welding was done with small variation of welding parameters around: Iv = 30 A, tv = 0,05 s, If = 5 A, tf = 0,20 s, argon 4.8 shielding gas flow was 4 - 8 l/min.

Case 3: Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube









X – ray inspection showed unrepeatable welds when manual laser welding was done

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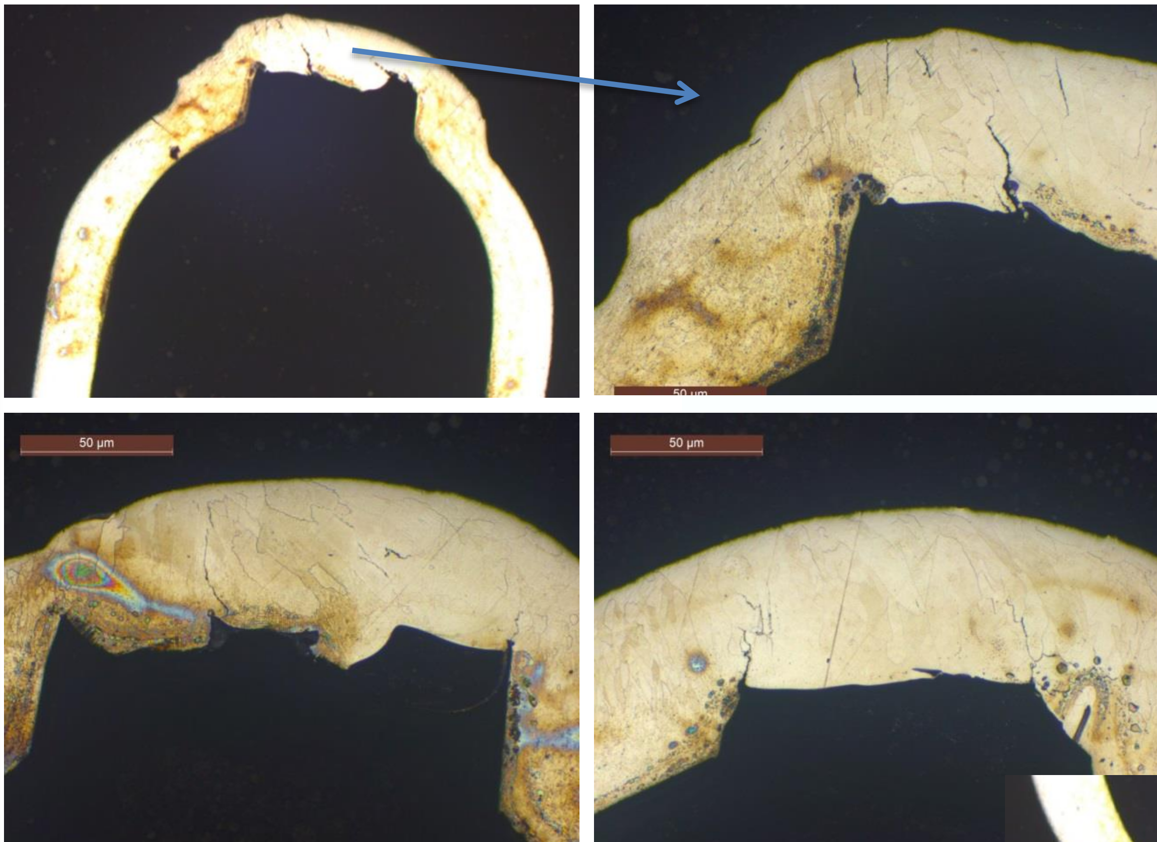
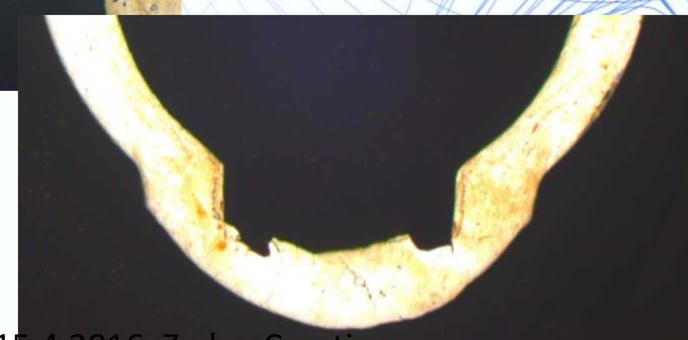
Case 3: Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube



Hot cracks are present due to excessive heat input

At manual laser welding unrepeatable welds were obtained



Nd-YAG laser, Pulse peak power 5,5 kW; pulse time: 4 ms

Case 3: Comparison of TIG, plasma and laser welding of a joint in a heating element between (Kanthal AF) and Inconel 601 tube

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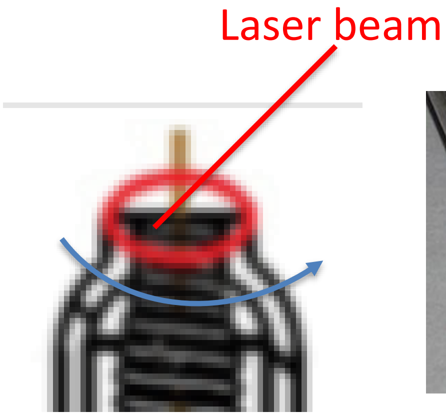
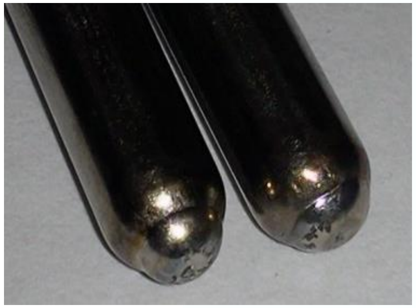
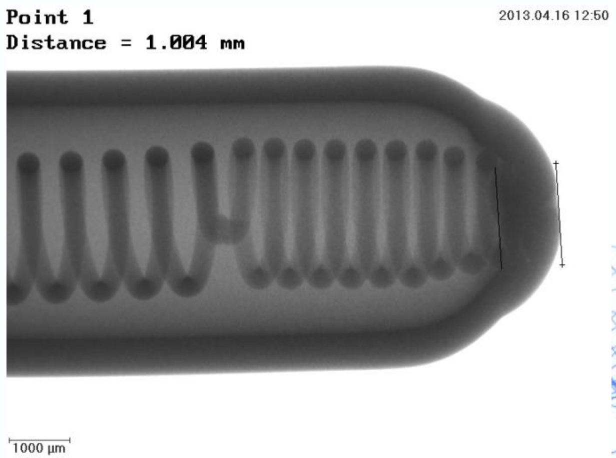
A automated laser beam welding was used to obtain repeatable welds:







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Conclusions

- Laser beam is a very good tool for welding. It enables a successful solving of weldability challenges.
- In order to achieve high quality welding results a knowledge of welding, lasers and metallurgy must be combined.
- A high quality repeatable welds can be produced by laser welding at proper:
  - joint design,
  - automation of the process and
  - selection of laser welding parameters.

- Technological limitations in production of weld pieces can make the laser welding more expensive.

Thanks for your attention

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