Metal Structures

Laboratory V

Microstructures of metals

LABORATORY OBJECTIVE’S

Analysis of influence of chemical composition and heat treating on mechanical properties and internal structure of steel and aluminum;

Topic:

1. Observe steel samples under a microscope and compare with the catalog.

Internal structure of steel

Allotropy - existence of different form of chemical element, of different chemical or mechanical parameters. For example: carbon - graphite, diamond.

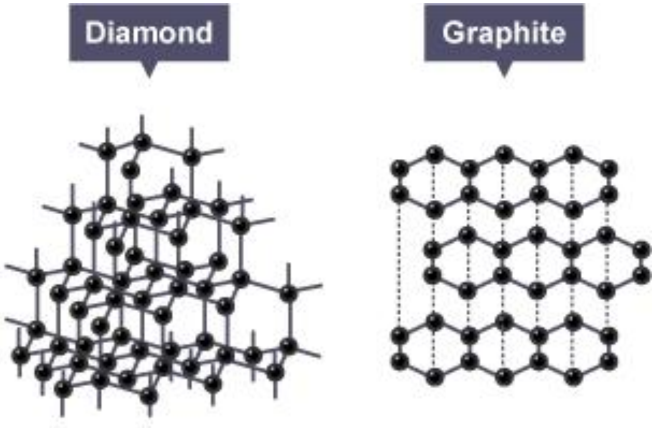

Photo: socratic.org

Photo: wiadomości.wp.pl

Iron:

α 0,286 nm

δ 0,293 nm

γ 0,365 nm

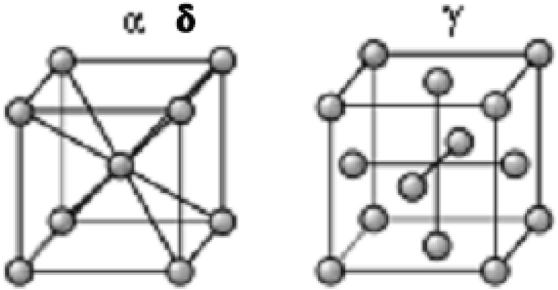

Photo: wikipedia

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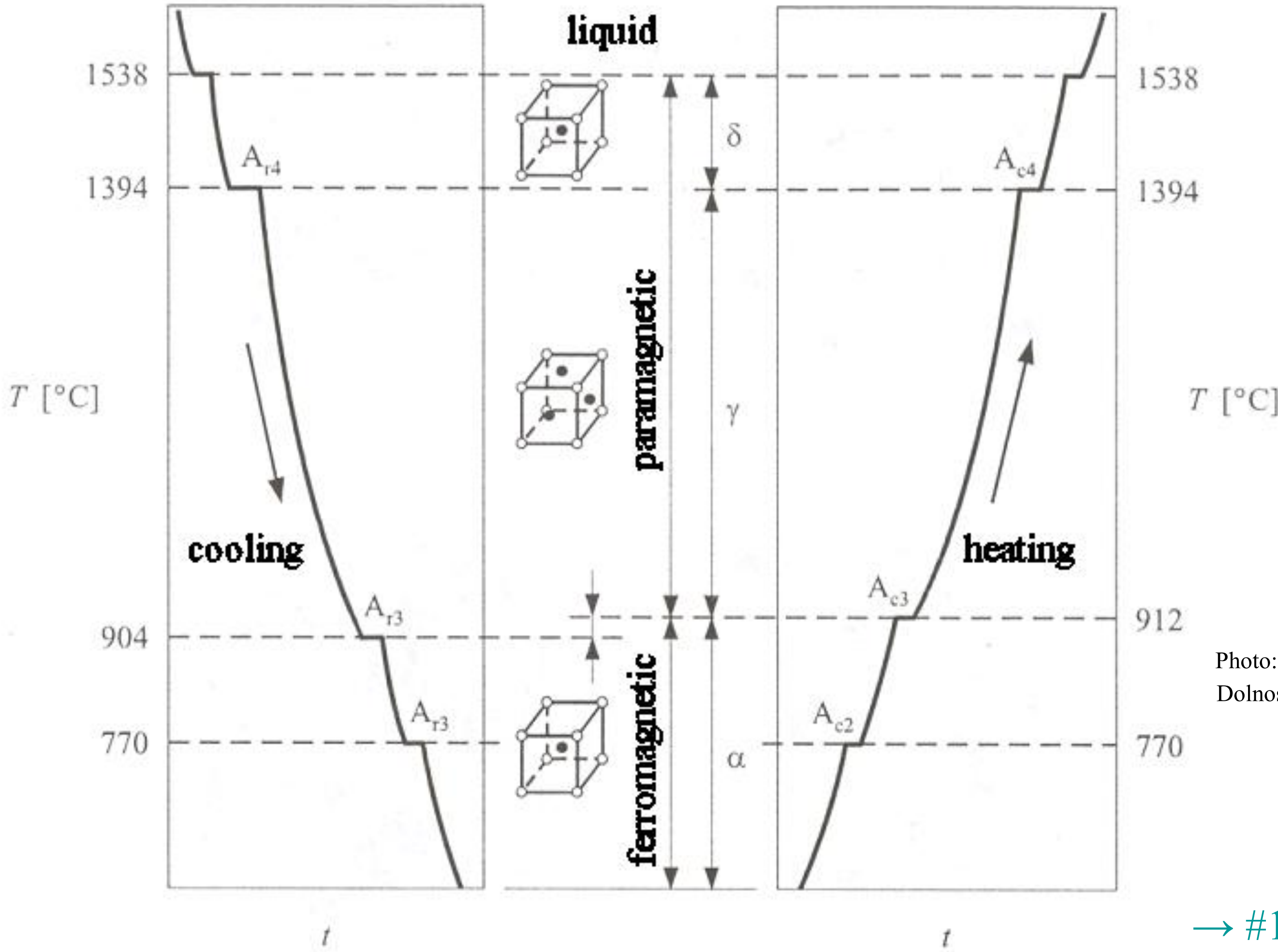

Photo: Konstrukcje stalowe, K. Rykaluk, Dolnośląskie Wydawnictwo Edukacyjne Wrocław 2001

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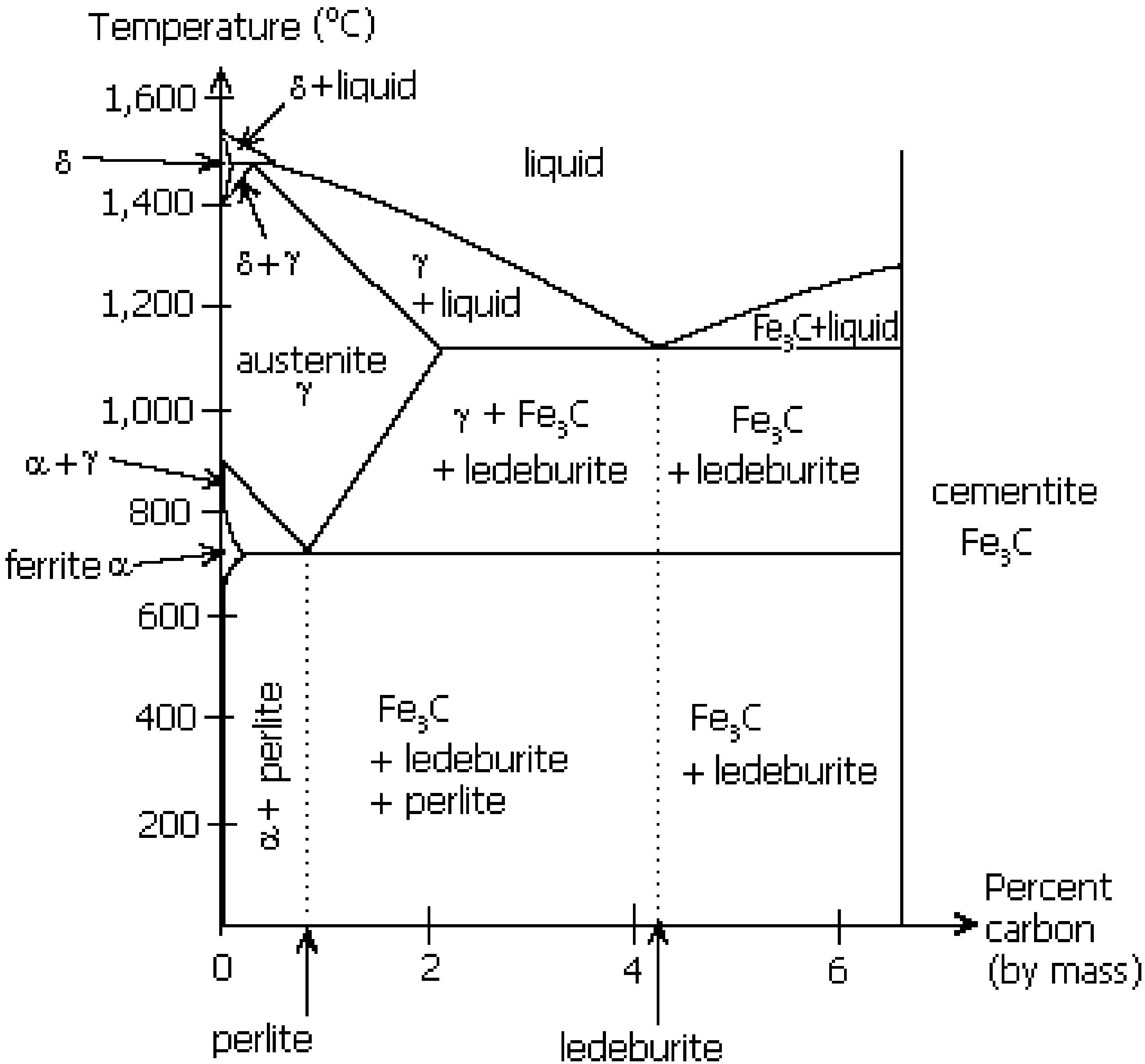

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Photo: wikipedia

Ferrite - α-Fe + C (solid solution)

Austenite - γ-Fe + C (solid solution, unstable → pearlite, bainite, martensite, sorbite)

Cementite - Fe_3C

Ledeburite = austenice + cementite

Pearlite = ferrite + cementite

Martensite - α-Fe + C

Bainite - similar to pearlite

Sorbite - similar to pearlite

Spheroidyte - balls of cementite in ferrite

More information → lab. #5

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Name	Mechanical parameters
Ferrite	Strong, plastic
Austenite	Very strong, very plastic
Cementite	Hard, fragile
Ledeburite	Hard, fragile
Pearlite	Finer structure → increase of strength and hardness
Martensite	Very hard, too fragile to be used as structure material
Bainite	Fragile, not very plastic, not very strong
Sorbite	Strong, plastic
Spheridoite	Strength and plasticity the lowest among different Fe-C systems

The best situation for structure steel: high strength, high plasticity, high hardness, very low fragility.

Definitions of these mechanical characteristics → Lec. #2

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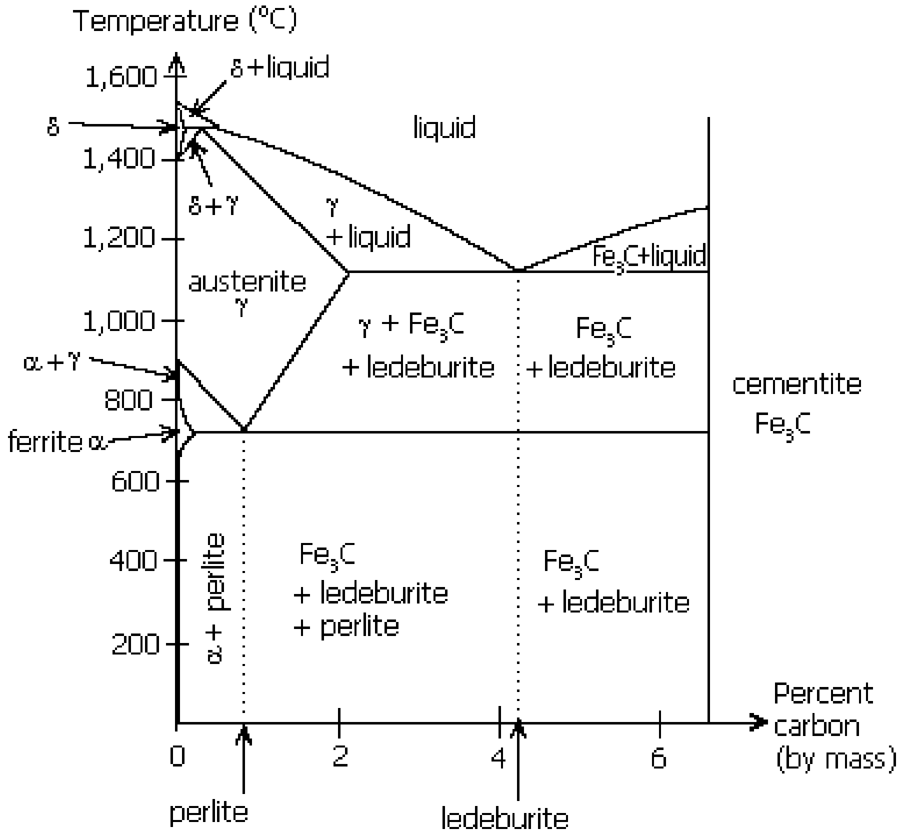
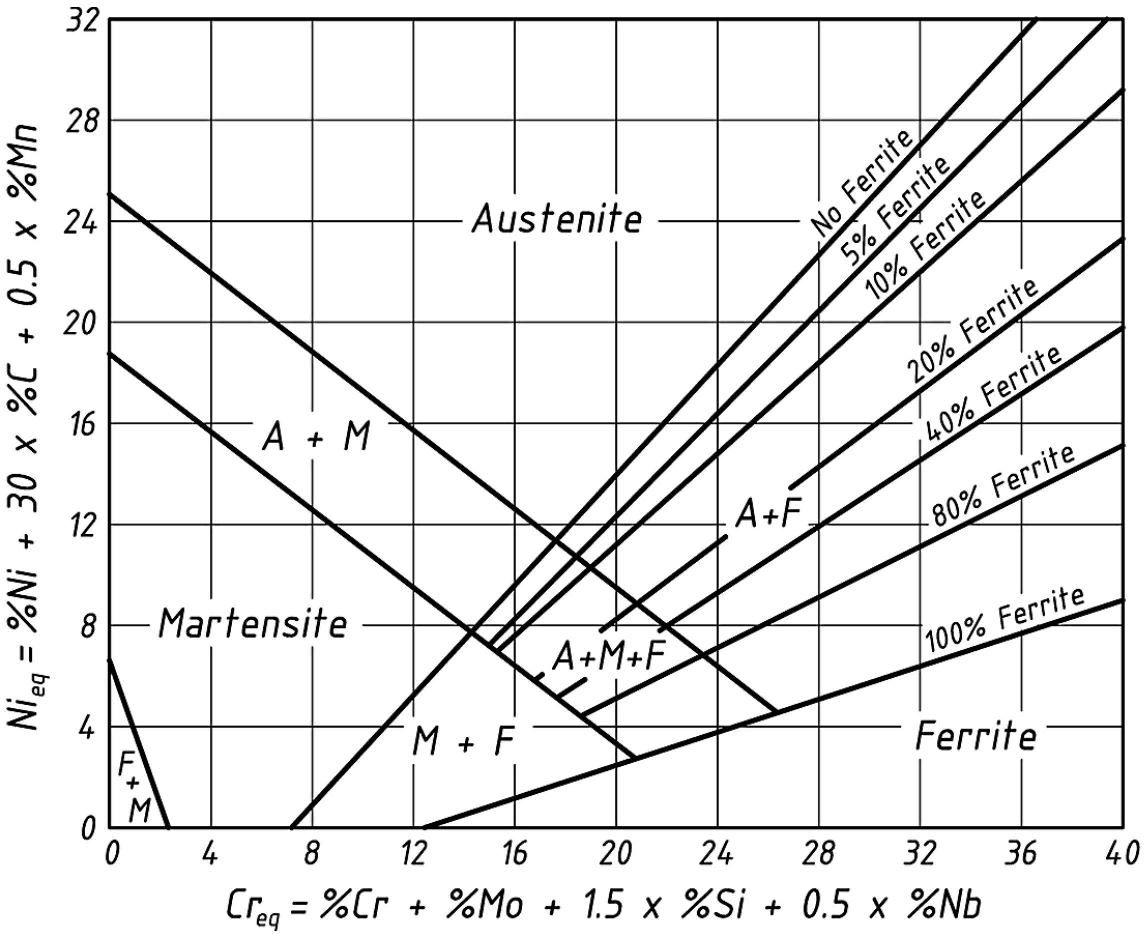


Photo: wikipedia

Types of internal structures, presented on diagram, exists only for „pure” situation, when in mixture are only Fe and C. According to diagram, austenite is unstable, changes into pearlite, bainite, martensite or sorbite and can’t exist in room temperature.

But there are many another chemical elements in various grades of steel. Presence of these alloying additives completely changes balance Fe-C.



For balance Fe-C important are proportion between various alloying additives, for example niobium equivalent and chrome equivalent. Alloying additives transform unstable fraction of steel to stable. The effect is permanent change of internal structure and change of mechanical parameters.

Photo: I. Tylek, K. Kuchta, Physical and technological properties of structural stainless steel, Technical Transactions 4-B / 2014

Element		Steel	Aluminum
Oxygen O	☠	Corrosion, reduction of C, S, P	Corrosion
Hydrogen H	☠	Fragility, cracking	Fragility, cracking
Nitrogen N	☠	Fragility, cracking	Fragility, cracking
Sulfur S	☠	Fragility, corrosion	
Phosphorus P	☠	Fragility, corrosion	→ #2 / 87
Iron Fe	👍	**Main component**	
Aluminum Al	👍	Reduction of O	**Main component**
Carbon C	👍	Hardness 👍 strength 👍 impact 👎 weldability 👎	
Chrome Cr	👍	Hardness 👍 strength 👍 grindability 👍 weldability 👎	
Copper Cu	👍	Corrosion resistance 👍	second essential ingredient
Magnesium Mg	👍		second essential ingredient
Manganese Mn	👍	Reducion of O and S	second essential ingredient
Molybdenum Mo	👍	Strength 👍 weldability 👎	second essential ingredient
Nickel Ni	👍	Hardness 👍 strength 👍 impact 👍	
Niobium Nb	👍	Weldability 👍	
Silicon Si	👍	Reduction of O hardness 👍 strength 👍	second essential ingredient
Titanium Ti	👍	Strength 👍	
Vanadium V	👍	Strength 👍 impact 👍 weldability 👎	
Zinc Zn	👍		second essential ingredient

Examples of chemical composition for diferent grades of steel (the most often used):

→ #2 / 88

Steel	C [%]			Si_{max} [%]	Mn_{max} [%]	P_{max} [%]	S_{max} [%]	N_{max} [%]	Cu_{max} [%]
	t ≤ 16 mm	16 < t ≤ 40 mm	t > 40 mm						
S235 JR	0,170	0,170	0,200	0,000	1,400	0,035	0,035	0,012	0,550
S235 J0	0,170	0,170	0,170	0,000	1,400	0,030	0,030	0,012	0,550
S235 J2	0,170	0,170	0,170	0,000	1,400	0,025	0,025	0,000	0,550
S275 JR	0,210	0,210	0,220	0,000	1,500	0,035	0,035	0,012	0,550
S275 J0	0,180	0,180	0,180	0,000	1,500	0,030	0,030	0,012	0,550
S275 J2	0,180	0,180	0,180	0,000	1,500	0,025	0,025	0,000	0,550
S355 JR	0,240	0,240	0,240	0,550	1,600	0,035	0,035	0,012	0,550
S355 J0	0,200	0,200	0,220	0,550	1,600	0,035	0,035	0,012	0,550
S355 J2	0,200	0,200	0,220	0,550	1,600	0,030	0,030	0,000	0,550

Conclusions:

- S235 → S275 → S355: increasing of strength ↔ increasing of amount of C, Si, Mn
- JR → J0 → J2: increasing of resistance for low temperatures (#2 /67 - 73) ↔ decreasing of amount of pollutions P, S, N

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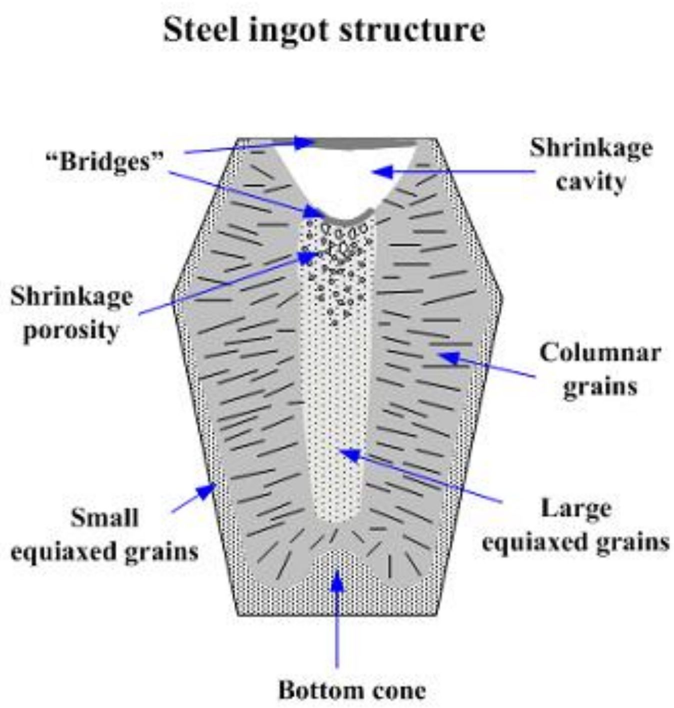

Photo: substech.com

Relationship: mechanical properties ↔ amount of C [%]

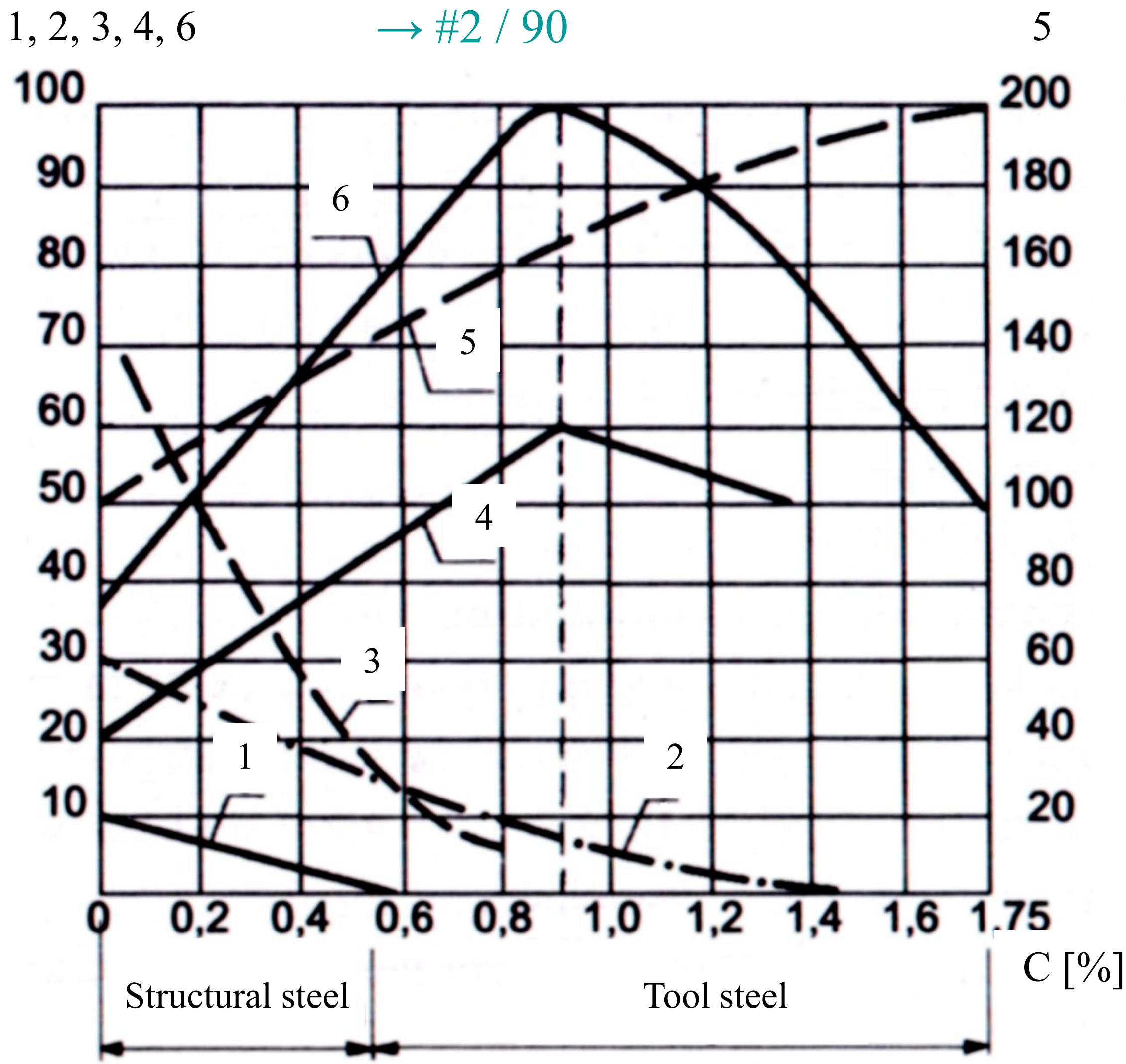

Photo: Łubiński M, Filipowicz A, Żółtowski W, "Konstrukcje metalowe", Arkady 2000

1. Impact resistane / 100 (left scale, [kJ / m^2]);
2. Elongation during testing, #2 / 12 (left scale, [%]);
3. Reduction of area during testing, #2 /18 (left scale, [%]);
4. f_y / 10 (left scale, [MPa]);
5. Brinell hardness (right scale, [MPa]);
6. f_u / 10 (left scale, [MPa]);

Second way to change internal structure is – besides chemical composition – heat treating. It is process (of few cyclic process) of change of temperature in very specific way. Generally, this is increasing (at a predetermined rate) of temperature, keeping this temperature per predetermined time and decreasing (at a predetermined rate) of temperature. The effect is change of internal structure of crystals (→ #t / 4), reduction of internal stresses and strains (in high temperature microcrystals easier to move, eliminating stress) and uniform distribution of the alloying additives within the interior of the steel member.

Change of mechanical parameters by heating and cooling steel. These precesses change internal structure of steel (recrystallisation). Speed of change of temerature is very important. Color change of the surface it is sometimes a side effect of this process.

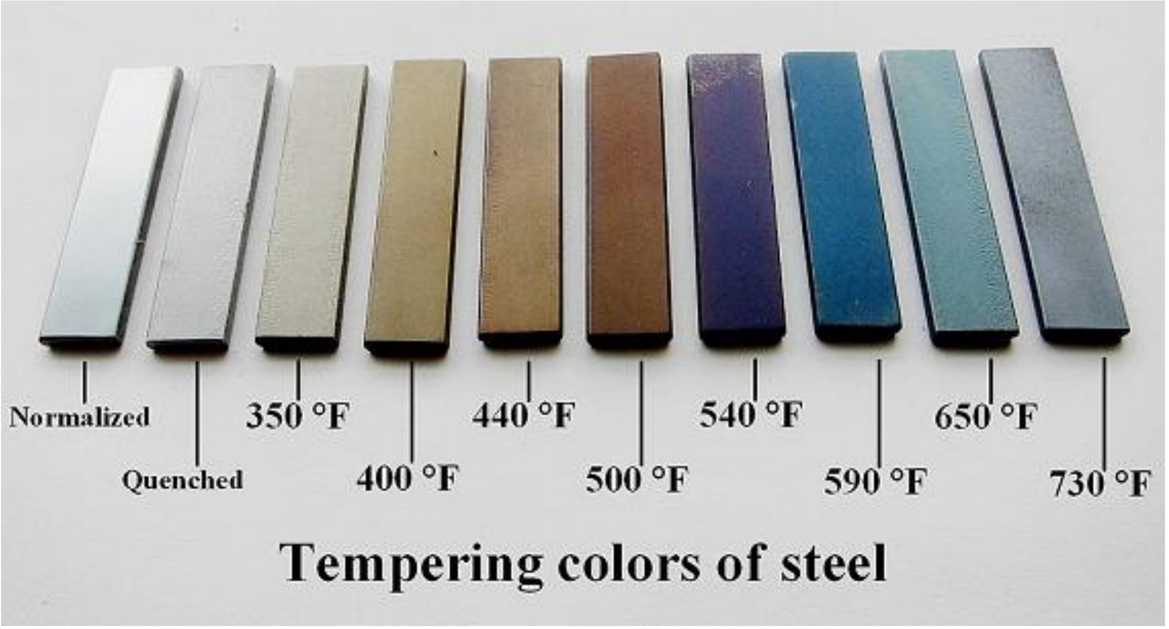

Photo: wikipedia

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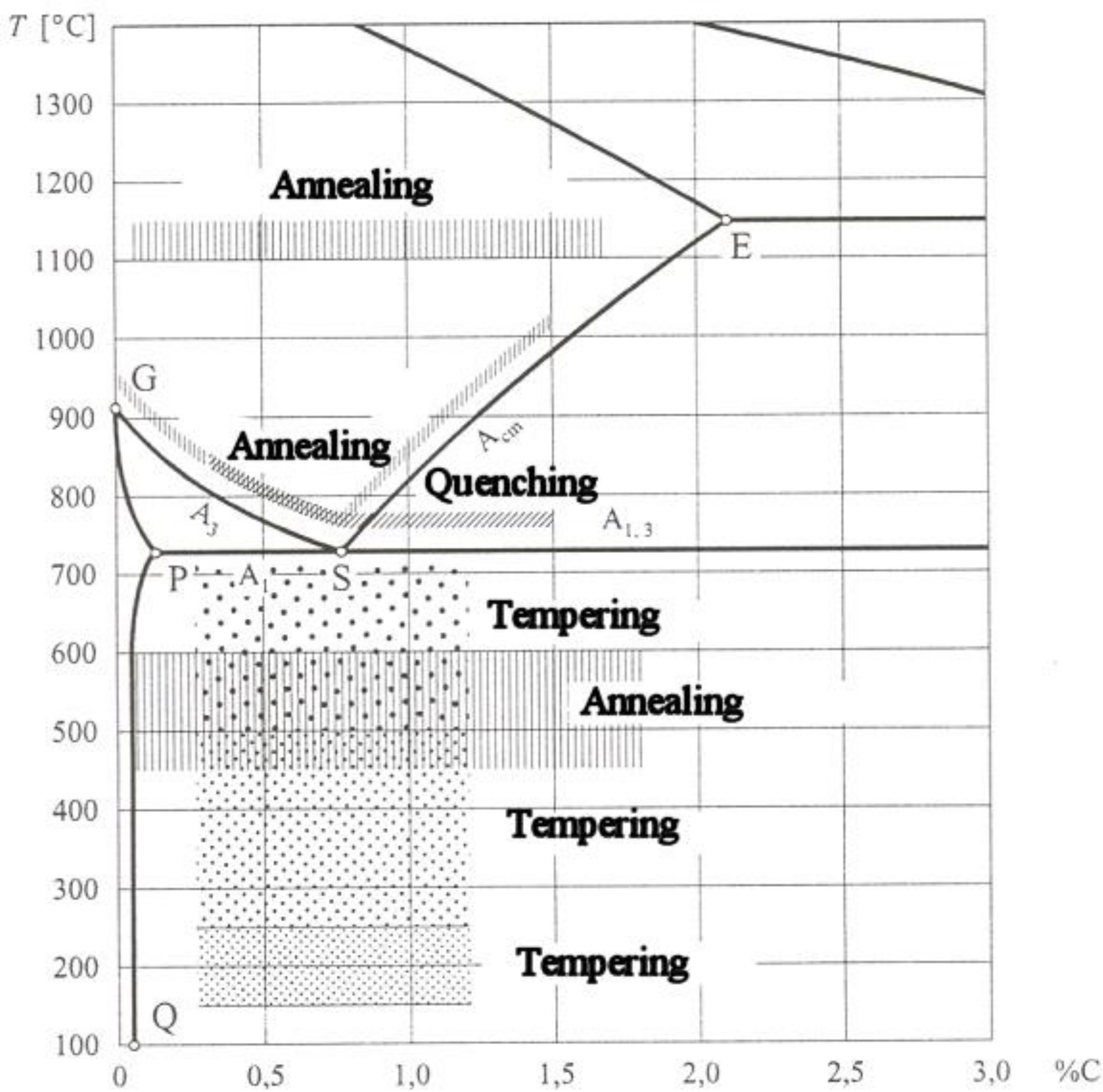

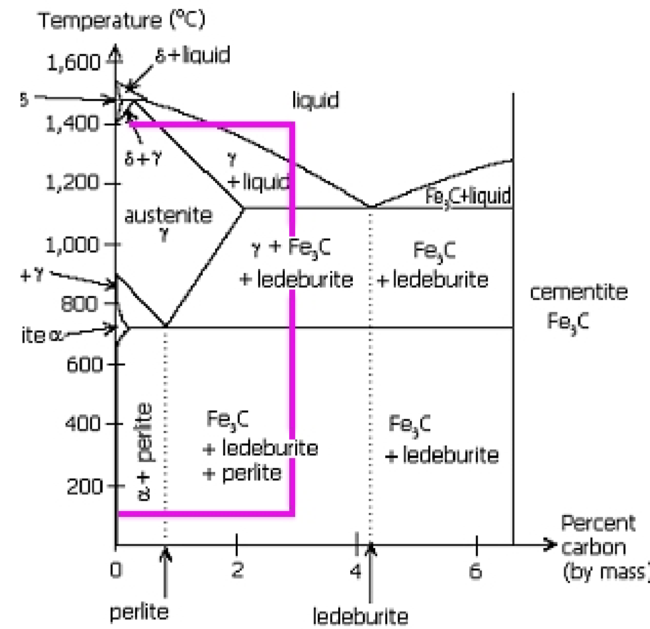

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Photo: Konstrukcje stalowe, K. Rykaluk,
Dolnośląskie Wydawnictwo Edukacyjne
Wrocław 2001

Annealing – increasing of temeprature, keeping element in this temperature for long time (it's need to change internal structure), very slow decreasing of temperature;

Annealing 1100° C → homogeneous internal structure (chemical and crystalline), homogenize the mechanical characteristics;

Annealing 800 - 100° C → fragmentation of crystals, increasing strength;

Annealing 500 - 600° C → reduction of residual stresses;

Quenching – increasing of temeprature, keeping element in this temperature for long time (it's need to change internal structure), very quick decreasing of temperature → increasing hardness and fragility;

Tempering – increasing of temeprature, keeping element in this temperature for long time (it's need to change internal structure), slow decreasing of temperature;

Tempering 600° C → high strength, decreasing hardness;

Tempering 400° C → high strength, high plasticity, decreasing hardness;

Tempering 200° C → reduction of quenching stresses and fragility, high hardness;

More information → lab. #5

→ #1 / 89

There is information for few cases (annealing 500 - 600° C, tempering 200° C) about reduction of residual / internal stresses. This type of stresses is dangerous for structure: calculation are made with fundamental assumption, that stresses in structure without load are equal 0. In real, there can be initial stresses of even big value. Sum of initial stresses and stresses from loads can destructs structure even for not very big value of load.

The origin of residual stresses:

- uneven cooling of hot-rolled sub-panels sections of varying thickness (→ #6 / 18-19);
- dragging of tension members (→ #2 / 30);
- deformations of microcrystals during rolling process (→ #6 / 23);
- plastic deformations in cold-formed sections (→ #6 / 20);
- welding residual stresses (→ #6 / 27).

There is information for few cases (annealing 1100° C, annealing 500 - 600° C) about change of crystallic structure (homogenizing, fragmentation). Small uniform crystals increase mechanical properties of steel.

The origin of heterogeneous crystal structure: each type of cold forming:

- dragging of tension members (→ #2 / 30);
- deformations of microcrystals during rolling process (→ #6 / 23);
- plastic deformations in cold-formed sections (→ #6 / 20);
- additionally, side effects of change of temperature during quenching;
- additionally, side effects of change of temperature during welding;

Influence of rolling on shape of cristals:

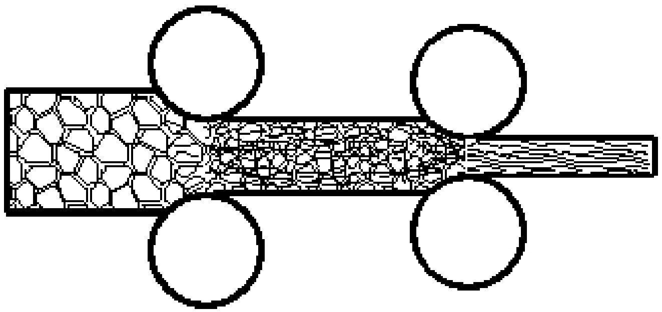


Photo: paws.wcu.edu

Influence of shape of cristals on mechanical parameters:

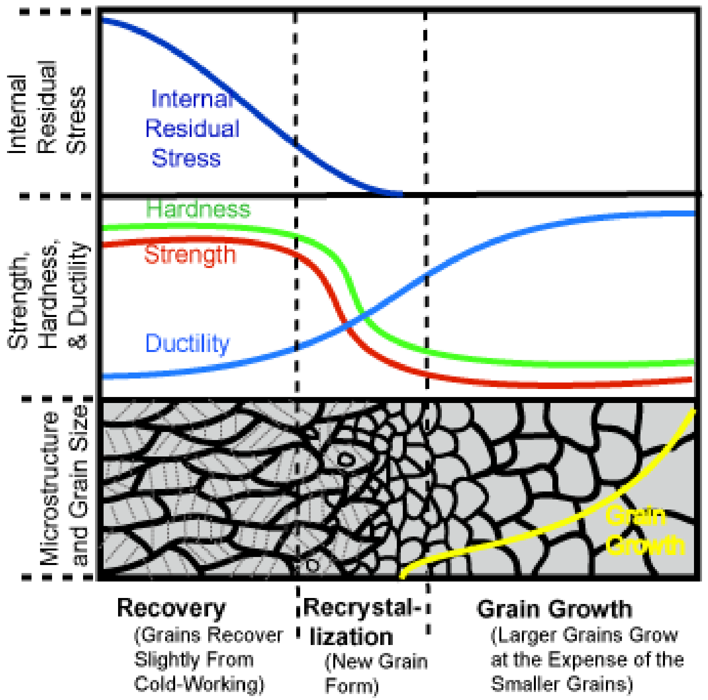
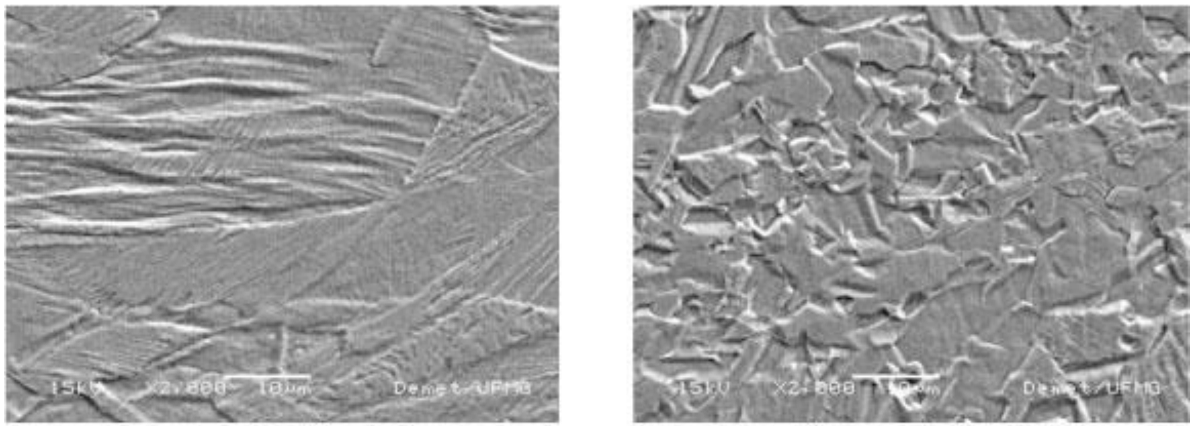


Photo: nde-ed.org

Example of effect of annealing: shape of cristals after cold-rolled of steel member and the same member after annealing; completely change of shape of cristals.



(a) Cold-rolled (b) Annealed at 850ºC

Photo: scielo.br

Example of interaction between cold-roling and annealing:

a. initial microstructure;

b. after second rolling;

c. after fourt rolling;

d. after fourth rolling + 2 h annealing 550 ^{o}C.

1. large grain of cementite in pearlite;
2. small grains of cementite in pearlite
3. lamellas of cementite in pearlite

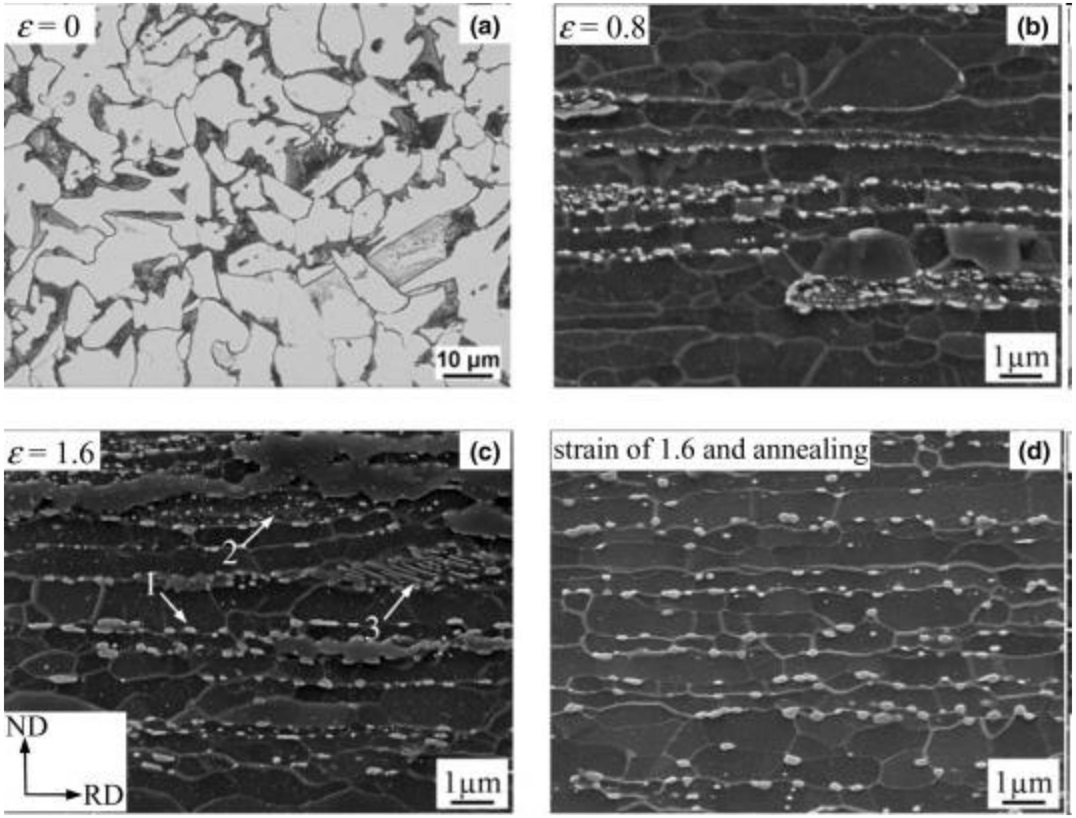


Photo: researchgate.net

Example of interaction between cold-rolling and annealing:

a. initial microstructure;

b. after first rolling;

c. after second rolling;

d. after third rolling;

e. after fourth rolling;

f. after fourth rolling + 2 h annealing 550 ^{o}C.

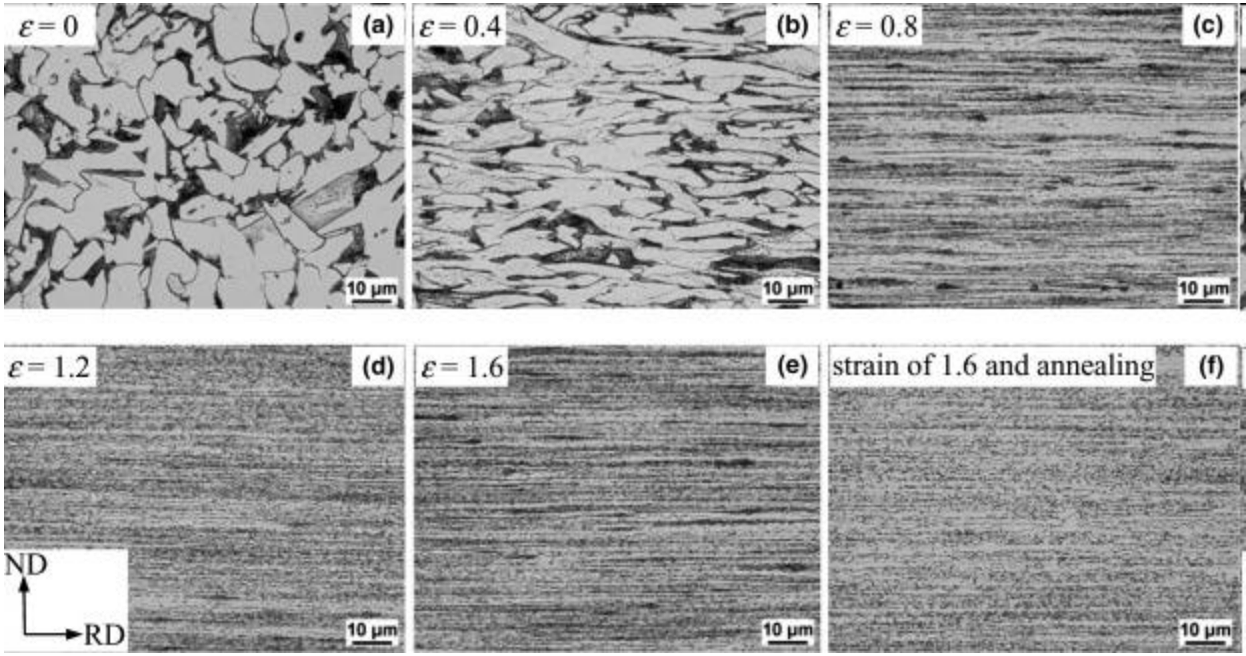


Photo: researchgate.net

Photo: homemetalshopclub.org

During hardening and quenching, martensitic transformation occurs and the formation of martensite.

Impact of tempering on martensite:

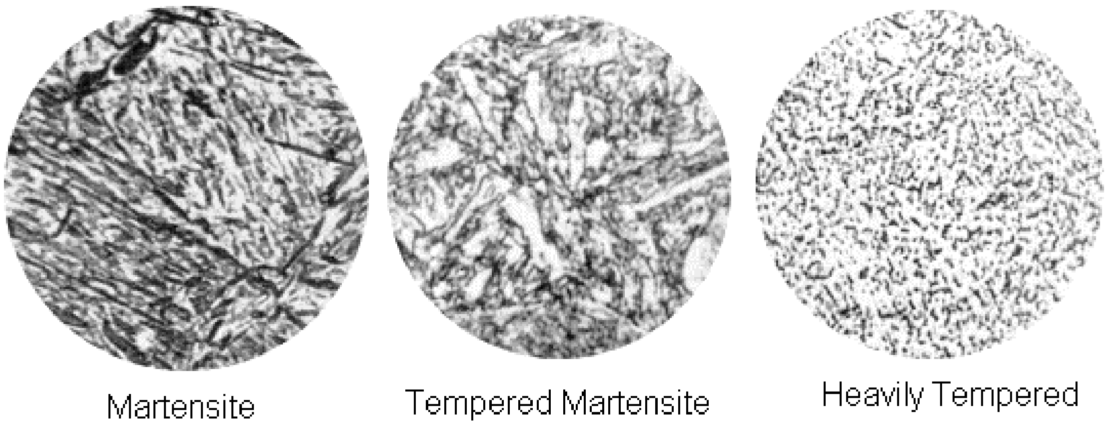


Photo: gowelding.com

As in the case of steel, alloying elements are added to aluminum alloys.

Alloying elements → lec. #2

There is very important type of "heat treating" for aluminium: precipitation hardening (age hardening). The effect of process is increasing of strength and decreasing of plasticity. Increasing of aluminum strength can be up to few dozens %.

Precipitation hardening is devastated during welding. Because of this, heat affected zones (HAZ) must be analysed during calculation of aluminum welding.

HAZ → lab. #2

→ #1 / 93

There is specific heat treatening for aluminum: precipitation hardening (age hardening). During a carefully controlled heating and cooling cycles, there is a specific crystallization of the alloy additives in aluminum.

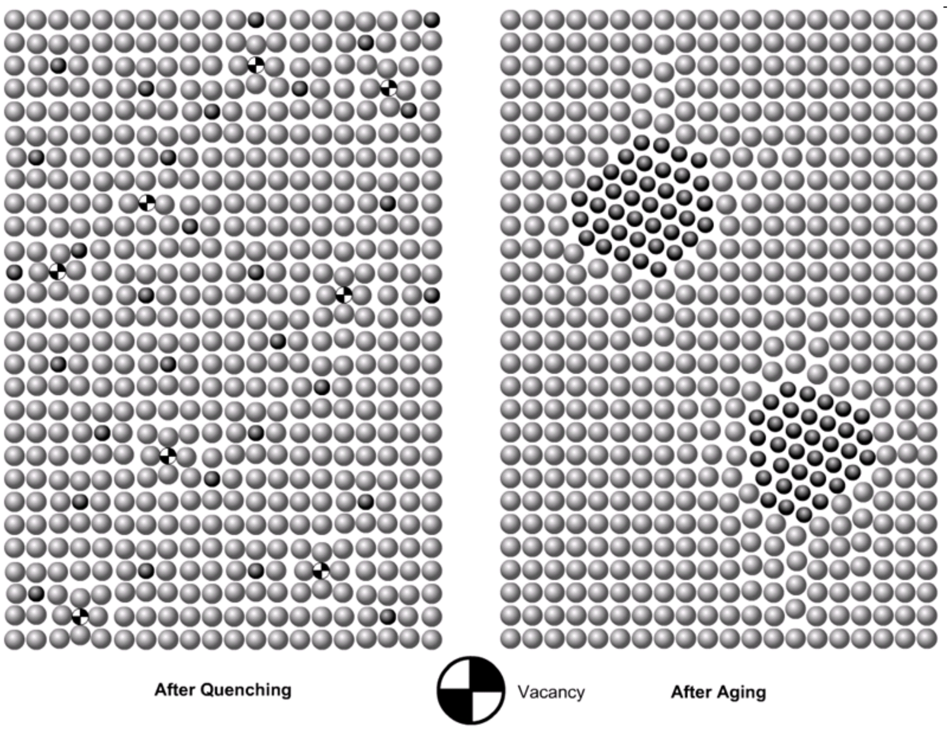


Photo: spaceflight.esa.int

Comparison of recrystallisation for various temperatures and various period of time of its action.

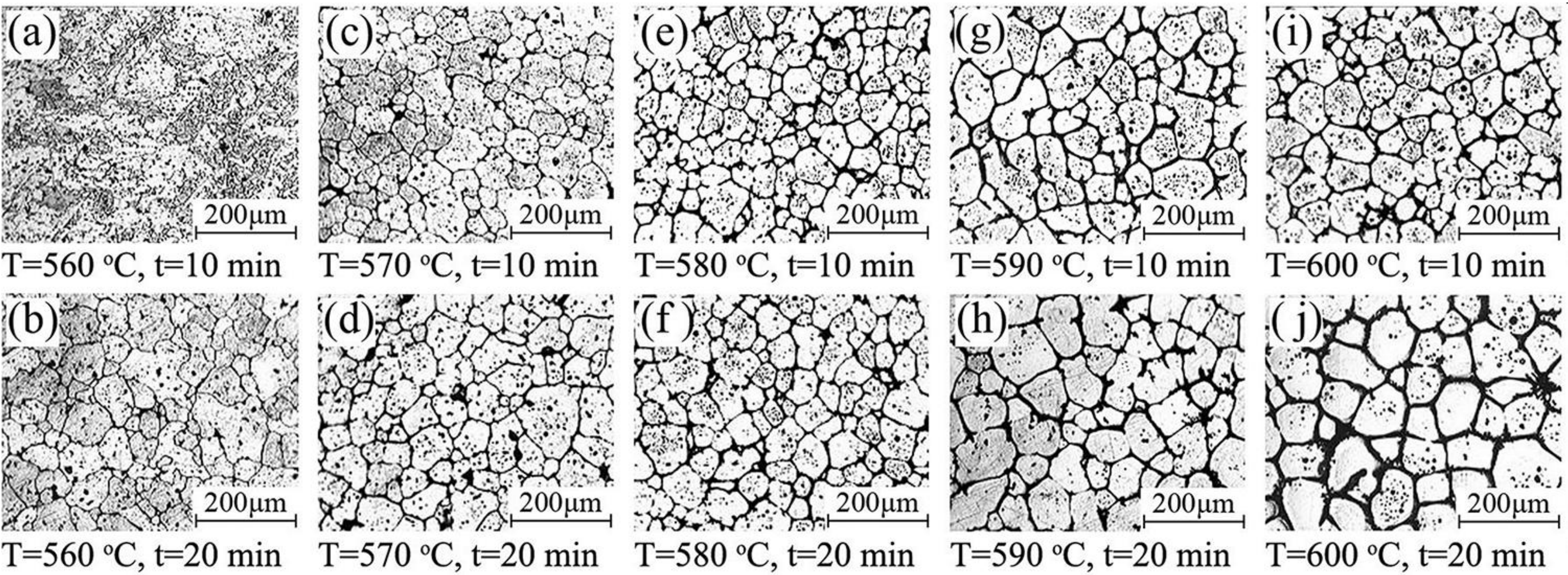


Photo: materialstechnology.asmedigitalcollection.asme.org

Concentrations of alloying additives block and limit deformations and shearing of cristals. Effects of precipitation hardening are decreasing of elongation and increasing of handness and strength.

Very distant analogy: reinforcement increases properties of concrete (reinforced concrete) by blocking of the deformation in tension zone.

Photo: phys.org

Photo: archiexpo.com

Each uncontrol action of temperatures (welding process, fire actions) completely devastates effects of precipitation hardening and decreases mechanical properties of aluminum alloys.

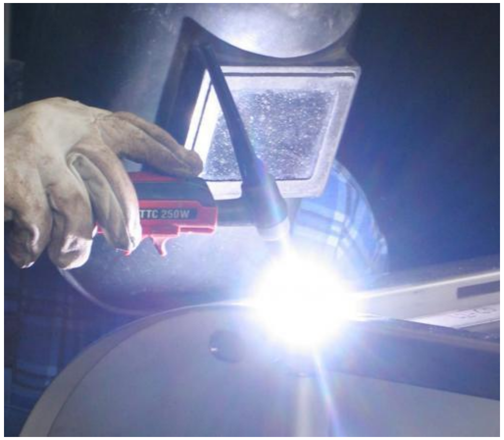


Photo: stelmet.net

Photo: easternontarionetwork.com

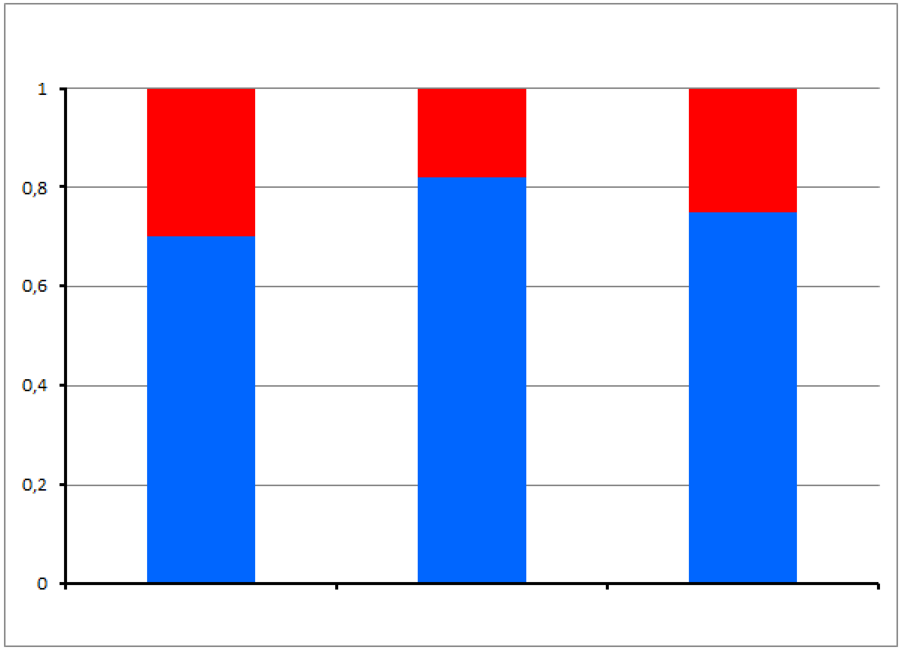
The measure of the susceptibility of aluminum alloys to the influence of temperature during welding are coefficients $\rho_{o,\,haz}$ and $\rho_{u,\,haz}$ (reduction of f_o and f_u at HAZ - head affected zone).

Values of these parameters are presented in EN 1999-1-1 tab. 3.2.

Alloy EN-AW	Temper [1)]	Thickness [1)] mm	f_o [1)]	f_u	A_{50} [1) 6)]	$f_{o,haz}$ [2)]	$f_{u,haz}$ [2)]	HAZ-factor [2)]		BC 4)	n_p 1), 5)
			N/mm²		%	N/mm²		$\rho_{o,haz}$ [1)]	$\rho_{u,haz}$		
3004	H14 | H24/H34	≤ 6 | 3	180 | 170	220	1 | 3	75	155	0,42 | 0,44	0,70	B	23 | 18
	H16 | H26/H36	≤ 4 | 3	200 | 190	240	1 | 3			0,38 | 0,39	0,65	B	25 | 20
3005	H14 | H24	≤ 6 | 3	150 | 130	170	1 | 4	56	115	0,37 | 0,43	0,68	B	38 | 18
	H16 | H26	≤ 4 | 3	175 | 160	195	1 | 3			0,32 | 0,35	0,59	B	43 | 24
3103	H14 | H24	≤ 25 | 12,5	120 | 110	140	2 | 4	44	90	0,37 | 0,40	0,64	B	31 | 20
	H16 | H26	≤ 4	145 | 135	160	1 | 2			0,30 | 0,33	0,56	B	48 | 28
5005/ 5005A	O/H111	≤ 50	35	100	15	35	100	1	1	B	5
	H12 | H22/H32	≤ 12,5	95 | 80	125	2 | 4	44	100	0,46 | 0,55	0,80	B	18 | 11
	H14 | H24/H34	≤ 12,5	120 | 110	145	2 | 3			0,37 | 0,40	0,69	B	25 | 17
5052	H12 | H22/H32	≤ 40	160 | 130	210	4 | 5	80	170	0,50 | 0,62	0,81	B	17 | 10
	H14 | H24/H34	≤ 25	180 | 150	230	3 | 4			0,44 | 0,53	0,74	B	19 | 11
5049	O / H111	≤ 100	80	190	12	80	190	1	1	B	6
	H14 | H24/H34	≤ 25	190 | 160	240	3 | 6	100	190	0,53 | 0,63	0,79	B	20 | 12
5454	O/H111	≤ 80	85	215	12	85	215	1	1	B	5
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Photo: EN 1999-1-1 tab. 3.2a

Reduction coefficients $\rho_{o, haz}$ and $\rho_{u, haz}$ describe reduction of mechanical properties after heat attack.



Total strenght according to EN 1991-1-1 tab. 3.2

Own strength = $\rho \cdot$ total strenght

Precipitation hardening

Photo: Author

Reduction factor for yeld strength ($\rho_{o, haz}$ for f_o) is equal 0,3 - 1,0. Own strength : 30% - 100%. Strength as the effect of precipitation hardening: 0% - 70%.

Reduction factor for ultimate strength ($\rho_{u, haz}$ for f_u) is equal 0,6 - 1,0. Own strength : 60% - 100%. Strength as the effect of precipitation hardening: 0% - 40%.

Strength of aluminum alloys comes mainly from special heat treating. High temperatures - for example during welding - devastate this effect.

Heat affected zones (HAZ) for aluminum - reduction of strength parameters as a result of welding

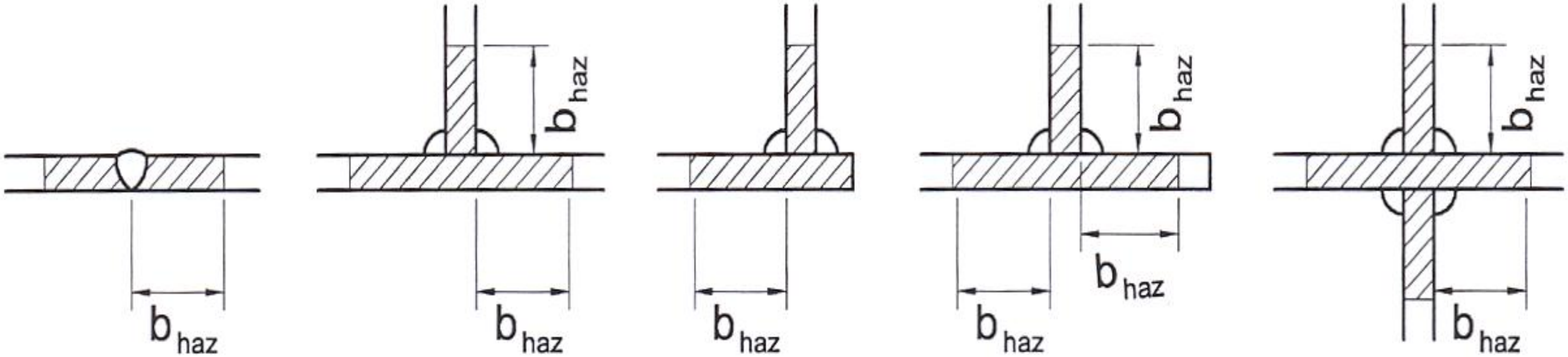


Photo: Author

Reduction factor

$1,0 \geq \rho_{haz} \geq 0,70$

→ Lab #2 / 14

Resistance R of cross-section is depend on geometrical characteristic X and strength f; ρ is reduction factor:

$$R = X \cdot f$$

For instability we must take into consideration reducted part of cross-section:

$$R = (X \cdot \rho_1) \cdot f$$

For welding joints in aluminum, strength of material locally decreases:

$$R = X \cdot (f \cdot \rho_2) = (X \cdot \rho_2) \cdot f$$

There is way of calculation for both phenomenon: **strength is the same** in each point of cross-section, but **geometry is reduced**:

→ Lab #2 / 15

$$R = (X \cdot \rho) \cdot f$$

We reduced geometry for different parts of cross-section in calculations:

- for steel welded I-beam we reduced width of elements, $d_{eff} = d_0\ \rho$
- for aluminum welded I-beam we reduced thickness of elements, $t_{eff} = t_0\ \rho$
- for cold-formed cross-sections we reduced thickness of elements, $t_{eff} = t_0\ \rho$

I[st] step

Welded zones

EN 1999-1-1 6.1.6.3 - effective cross-section for welds

(3) For a MIG weld laid on unheated material, and with interpass cooling to 60°C or less when multi-pass welds are laid, values of b_{haz} are as follows:

$0 < t \leq 6$ mm:	$b_{haz} = 20$ mm
$6 < t \leq 12$ mm:	$b_{haz} = 30$ mm
$12 < t \leq 25$ mm:	$b_{haz} = 35$ mm
$t > 25$ mm:	$b_{haz} = 40$ mm

→ Lab #2 / 77

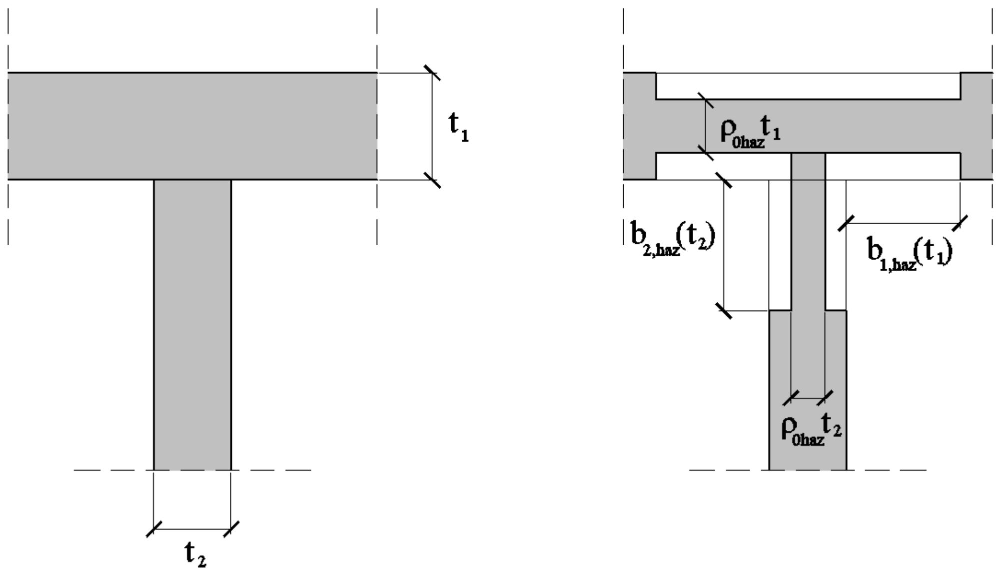


Photo: Autor

Task 1, 2, 3, 4 - identification based on catalogue, presented below.

MP8, 21, 41, 44, 51, M2 – steel

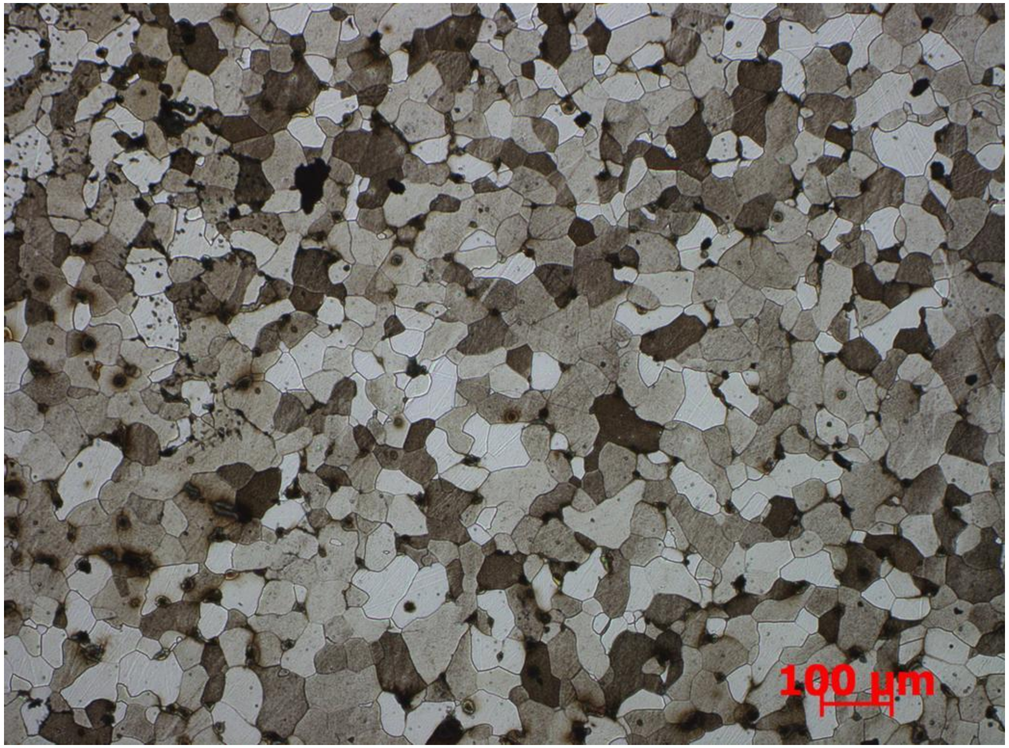
K, N6676, S1, N5324 – cast iron

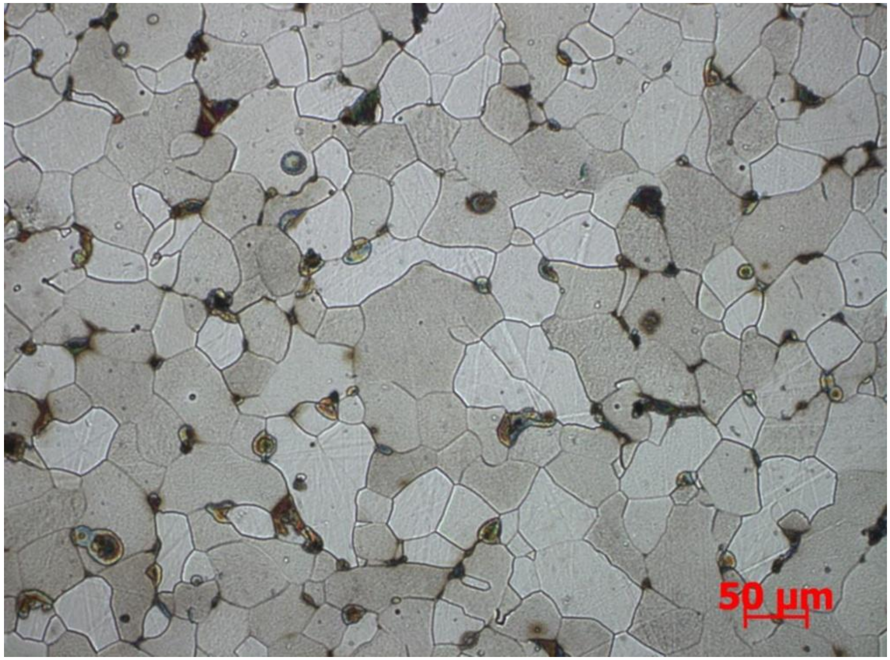
AK7, 11, 20 – aluminum

Similarities or differences of appearance may be due to different light intensity during photo.

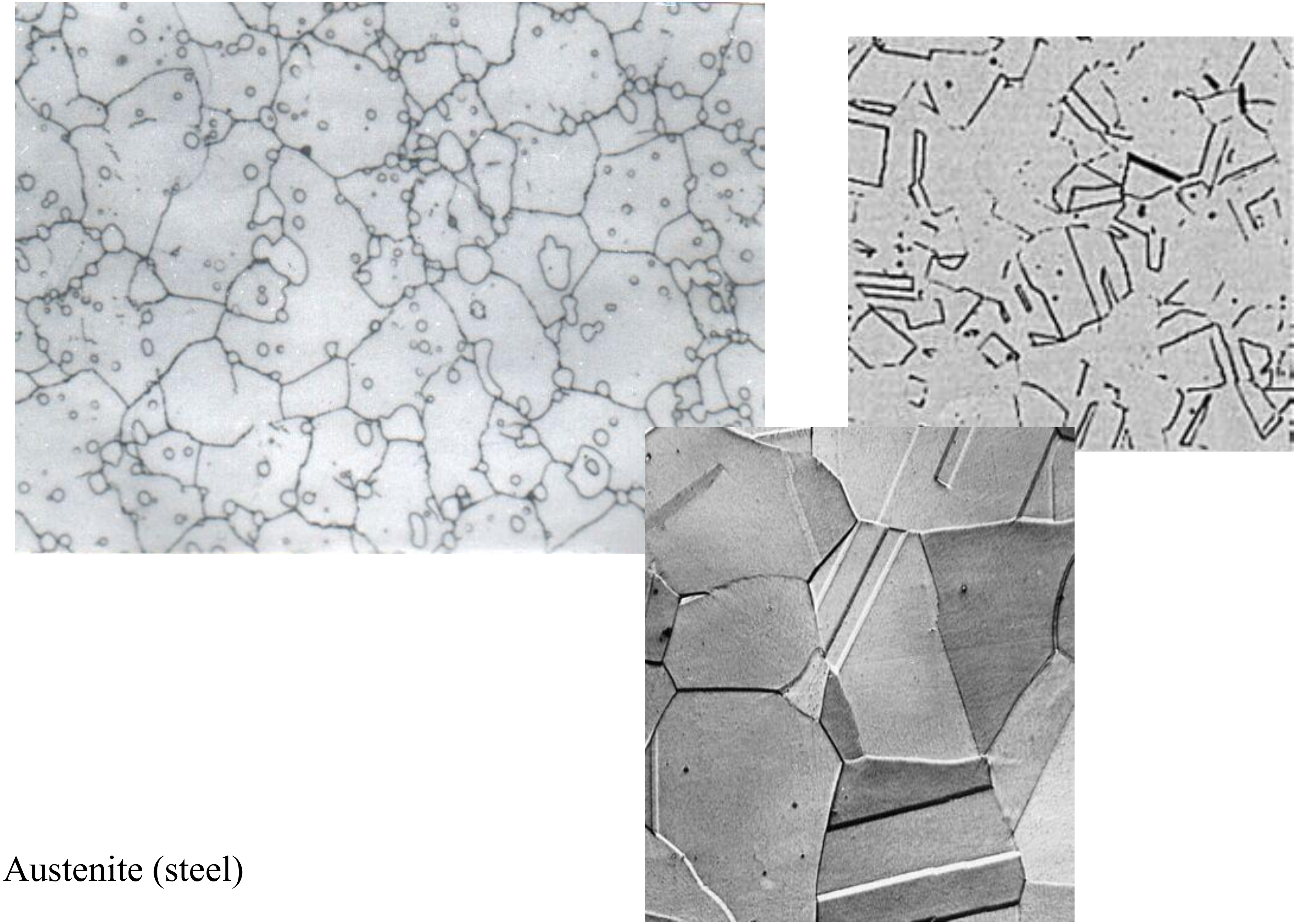
Photo:

aurhim.net ; msc Mirosław Boryczko, Cracow University of Technology ; canis_lups_silver@wp.pl ; corse76.altervista.org ; doitpoms.ac.uk ; flickrhivemind.net ; georgesbasement.com ; homemetalshopclub.org ; meetyoucarbide.com ; metalurgia.bblog.pl ; phys.org ; steeldata.info ; struktury.ilm.pl ; suw.biblos.pk.edu.pl ; phd Sławomir Szewczyk, Lublin University of Technology ; up.krakow.pl ; uqu.edu.sa ; wikipedia

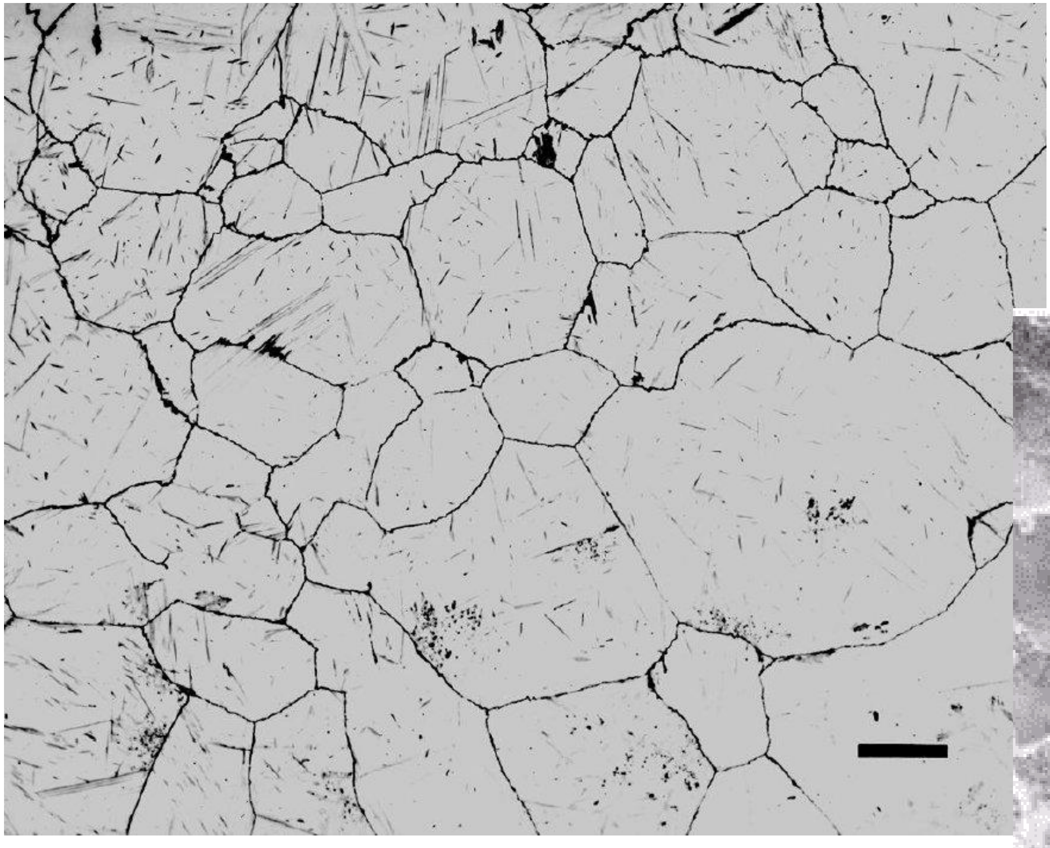




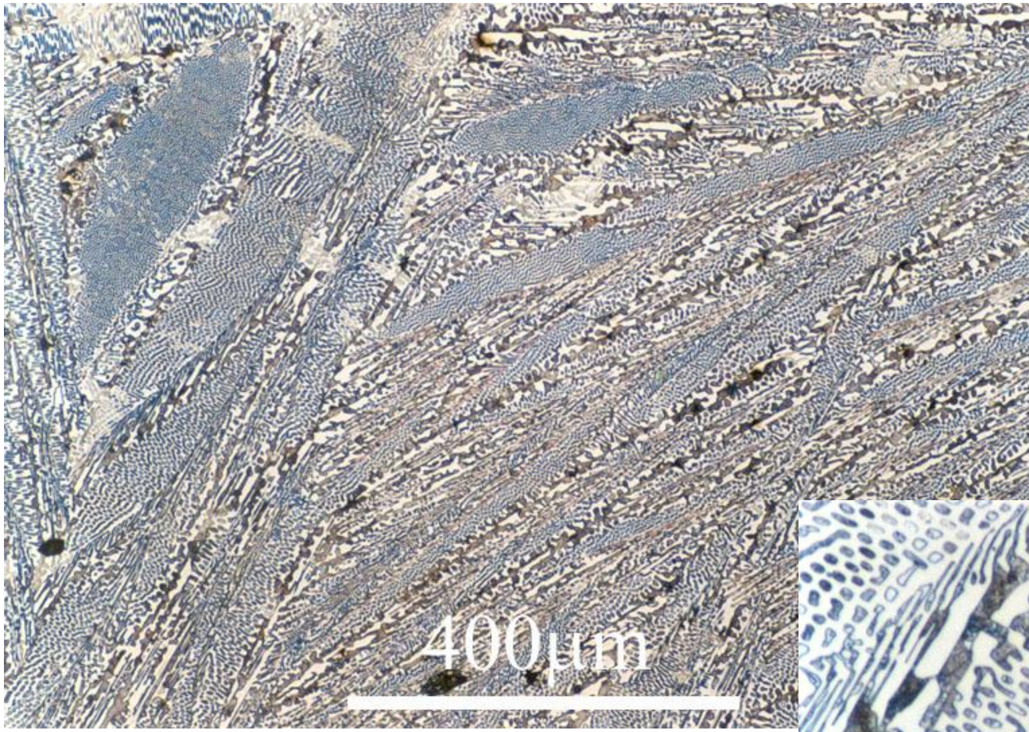
Ferrite (steel)

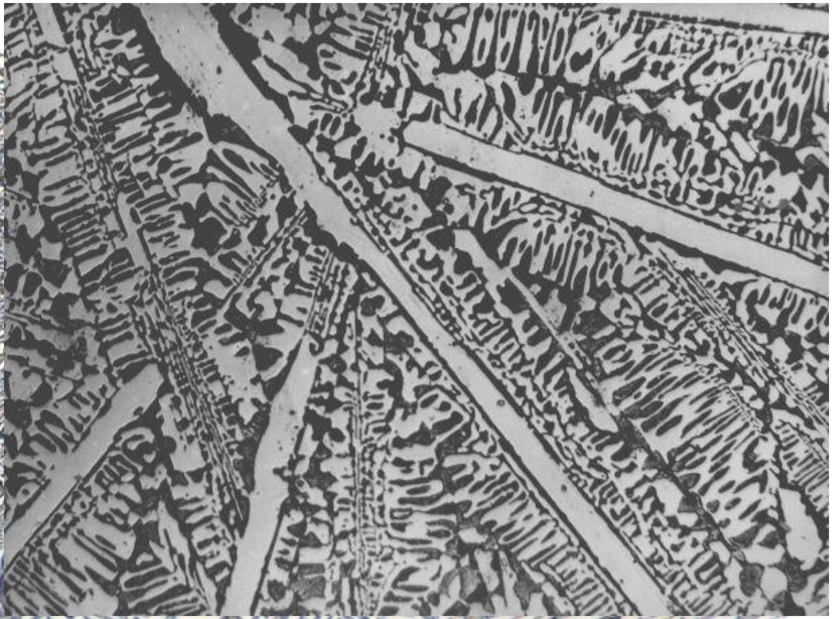


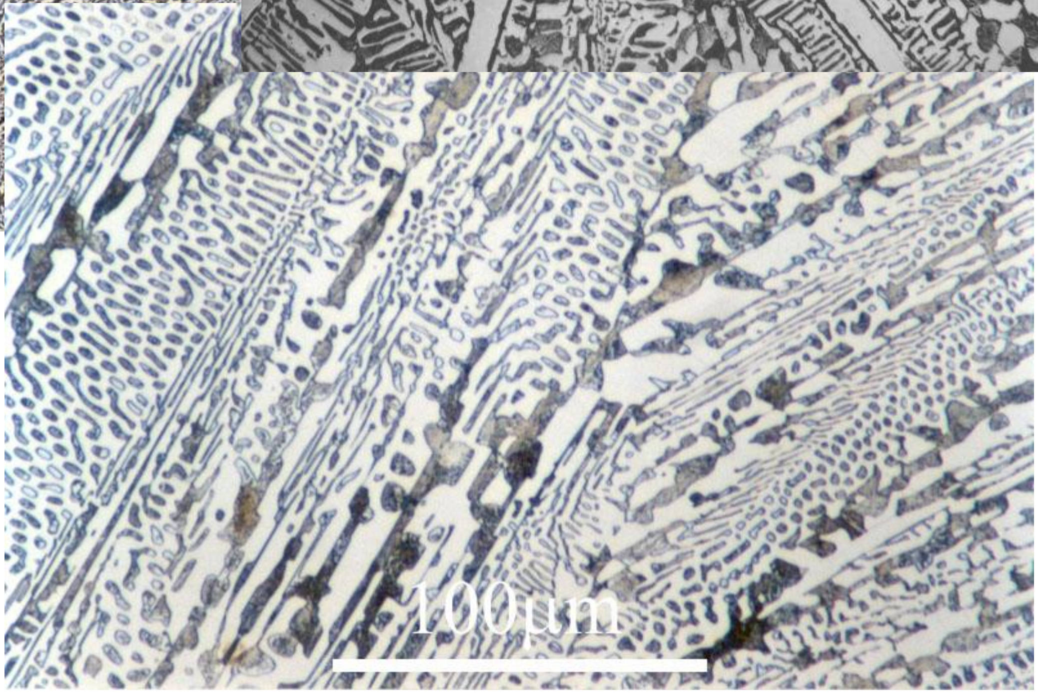
Austenite (steel)



Cemetite (steel)



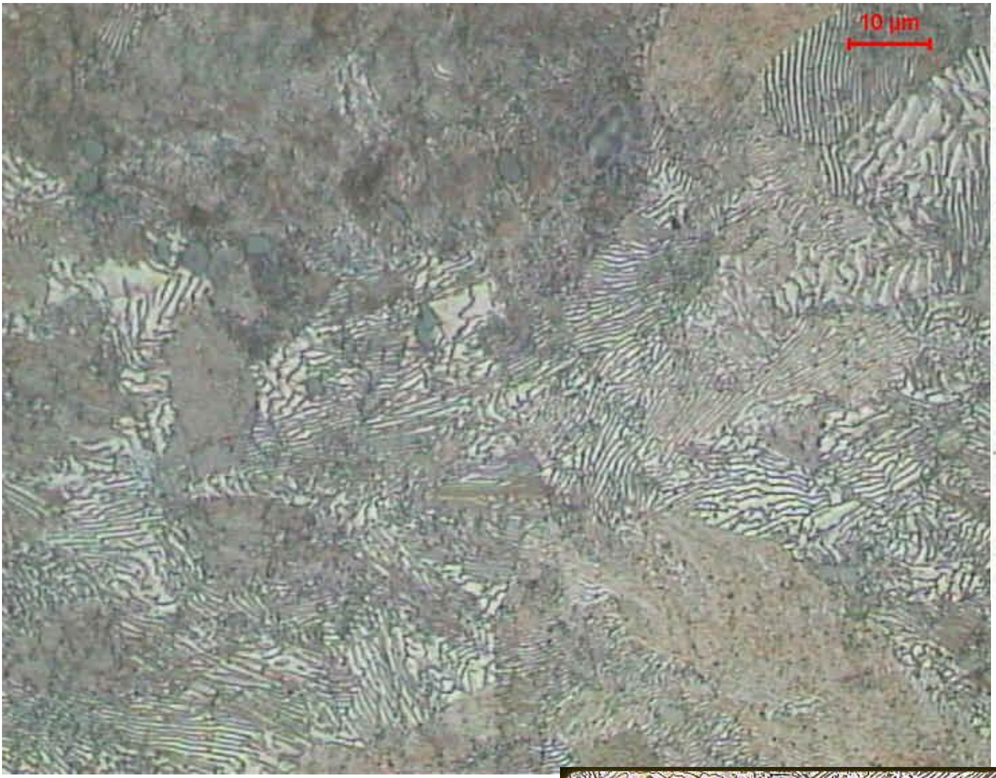


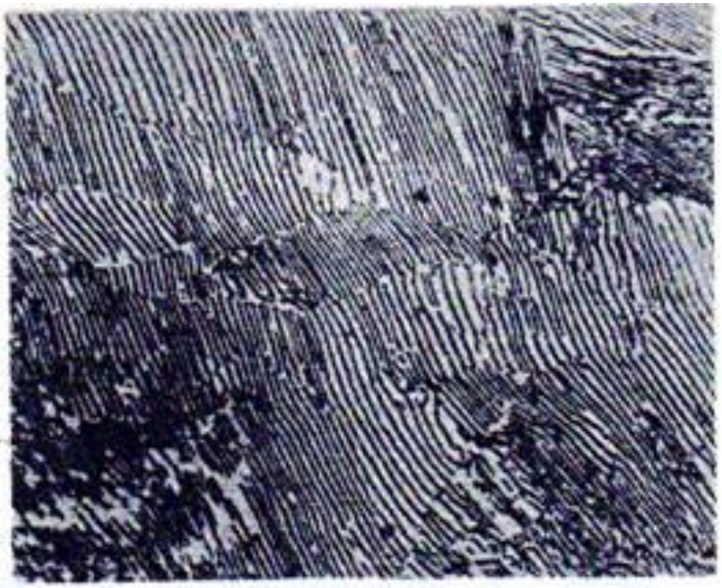


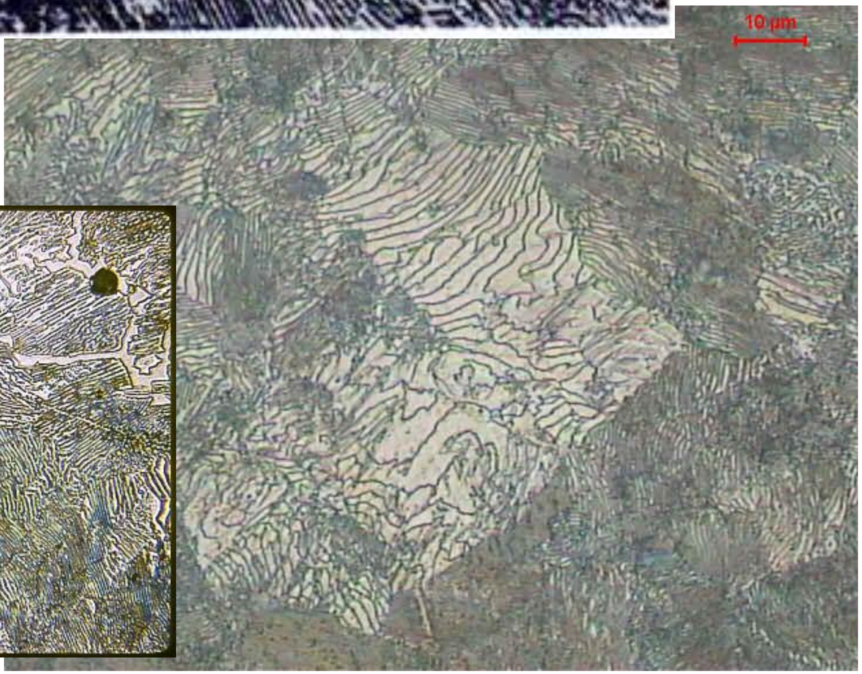
Ledeburite (steel)

dark – austenite

light - cementite



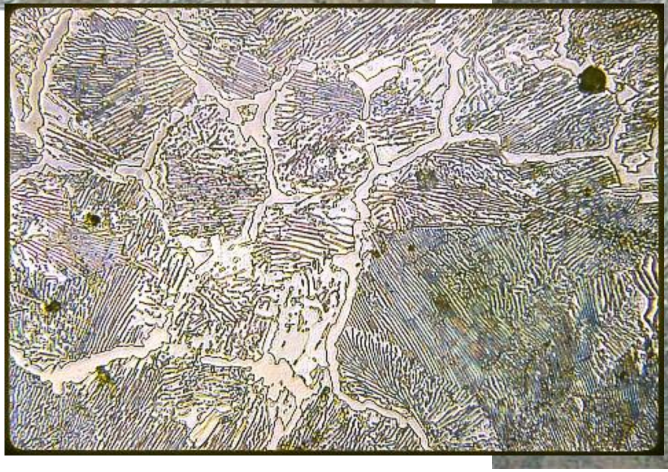


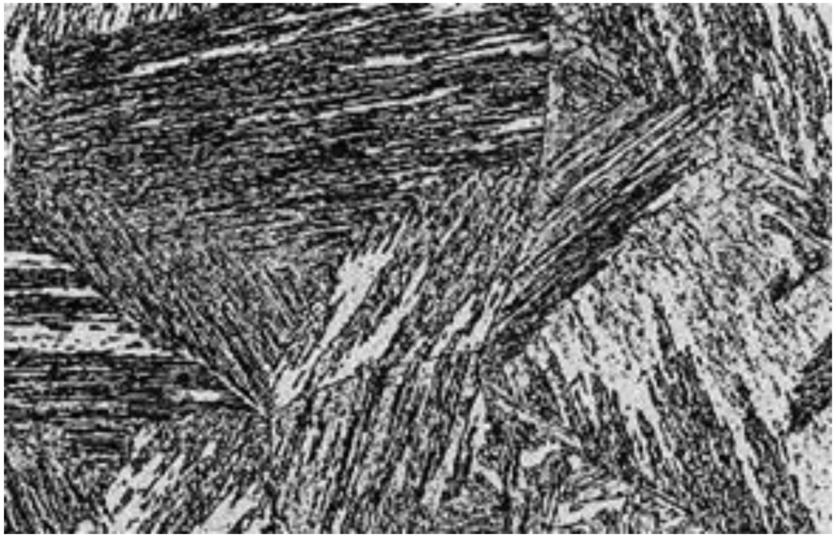


Perlite (steel)

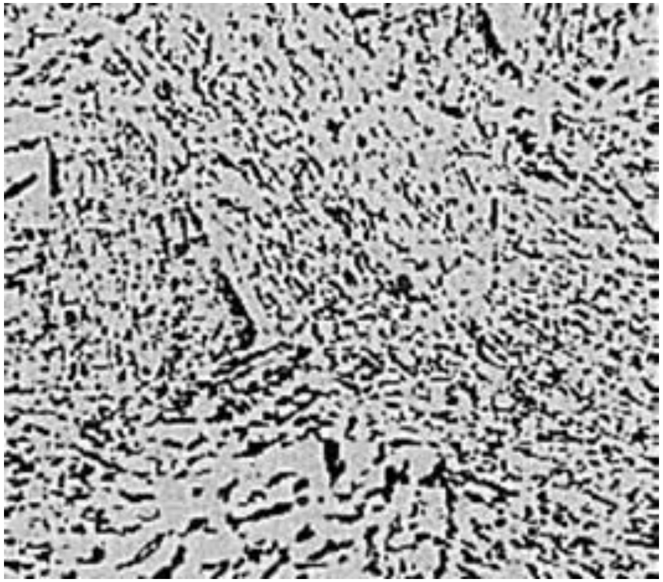
dark – ferrite

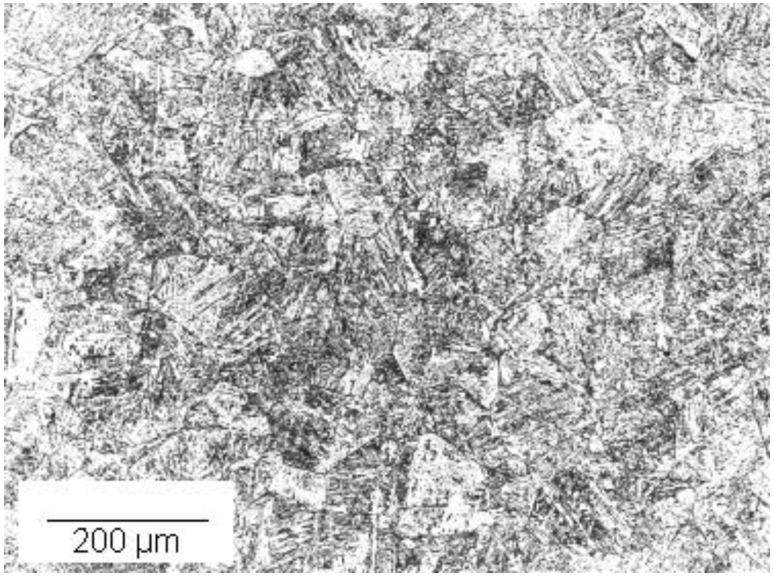
light - cementite



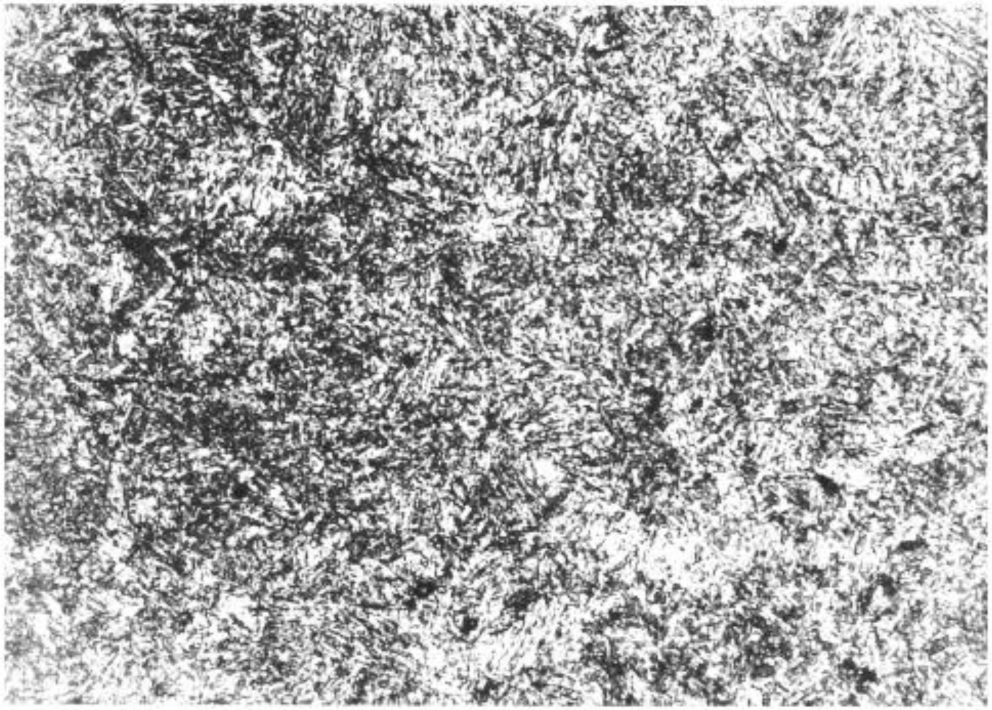


Martensite (steel)

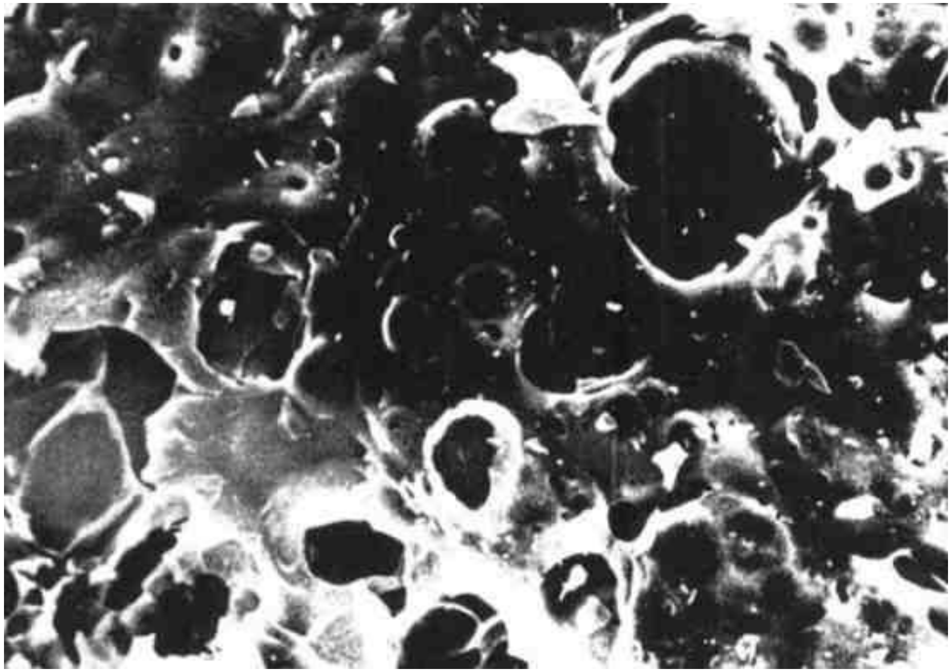


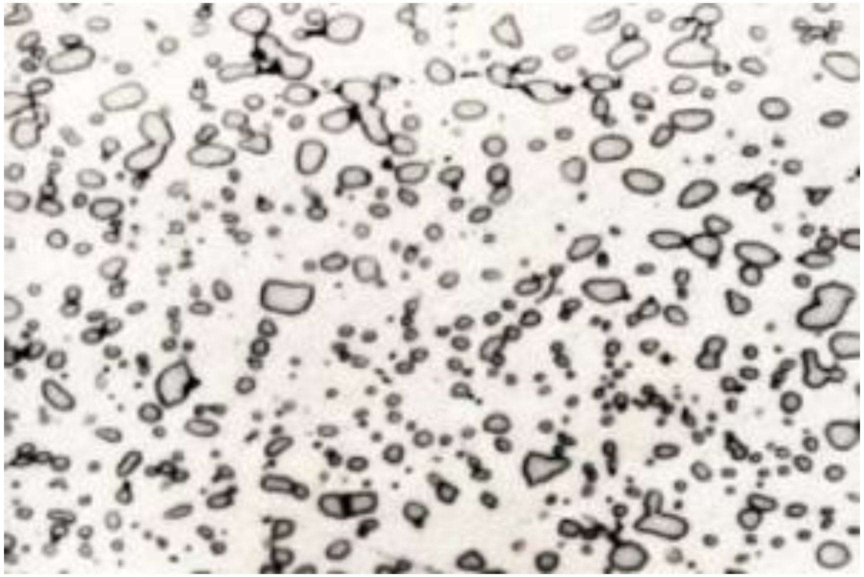


Bainite (steel)

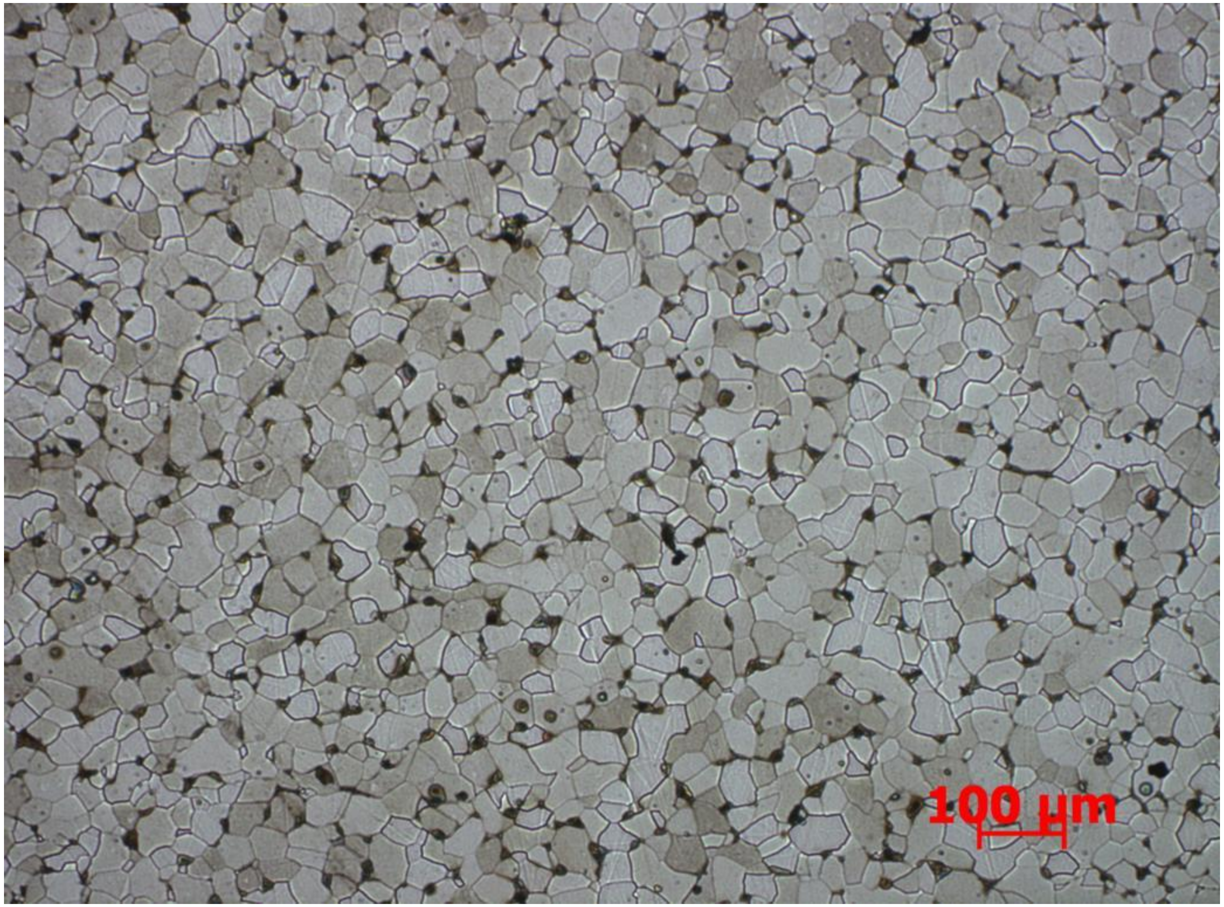


Sorbite (steel)

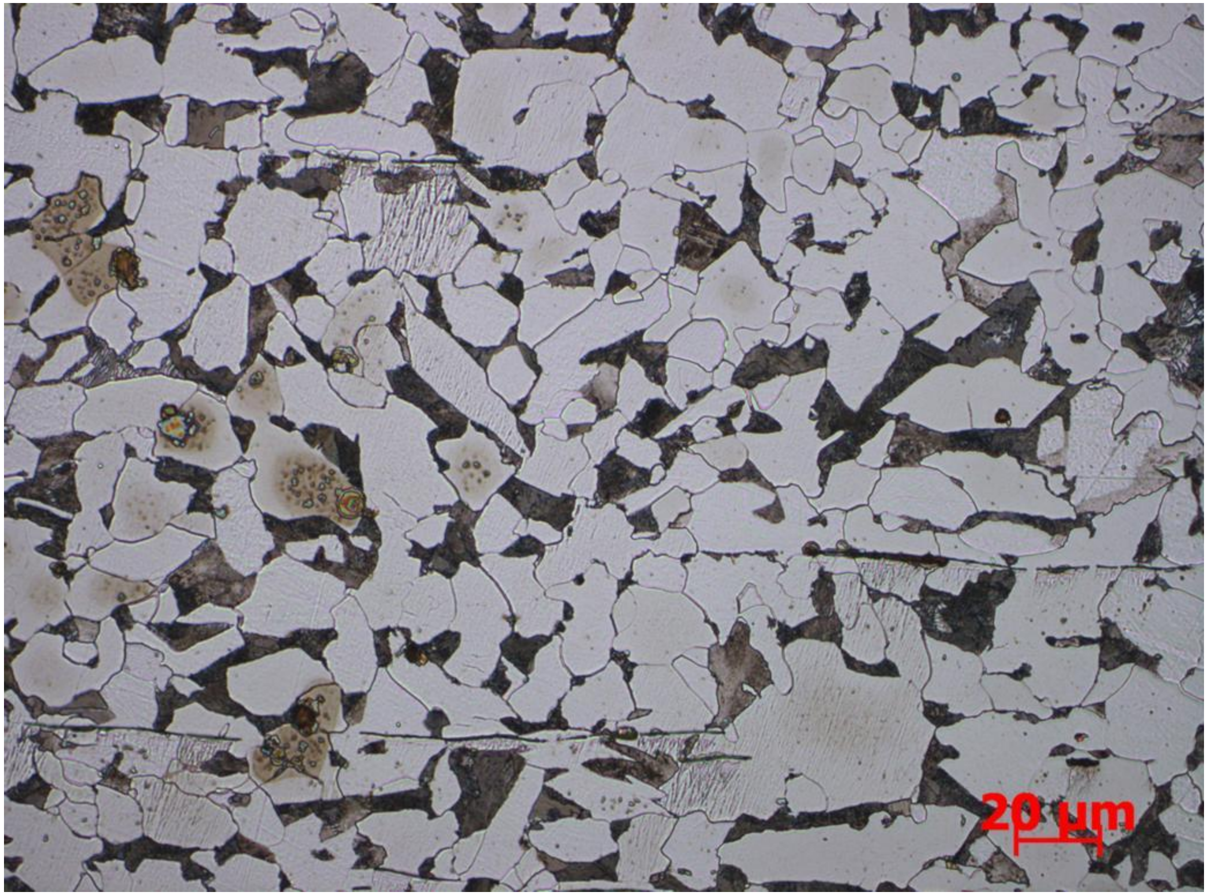




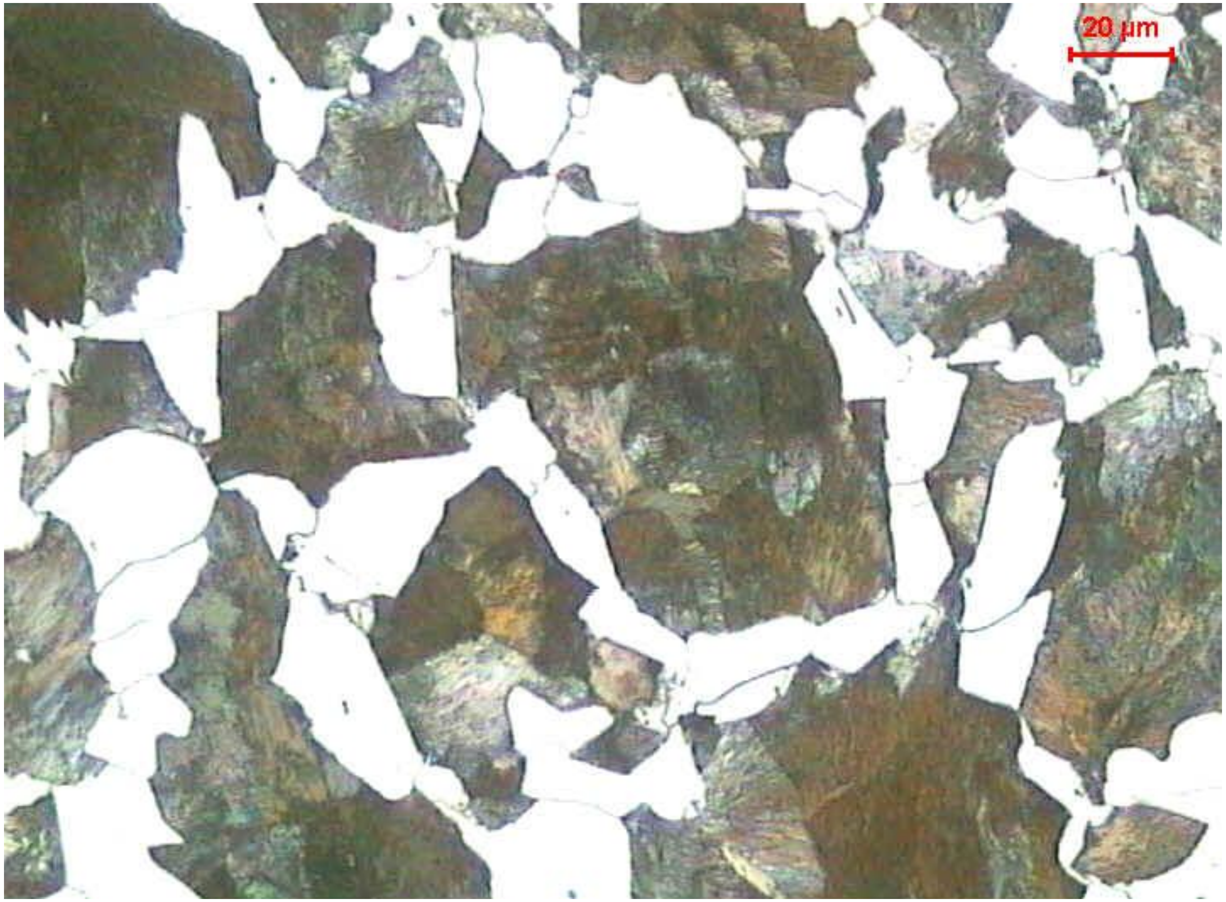
Spheroidite (steel)



Pure ferrite + little quantity of perlite (steel)

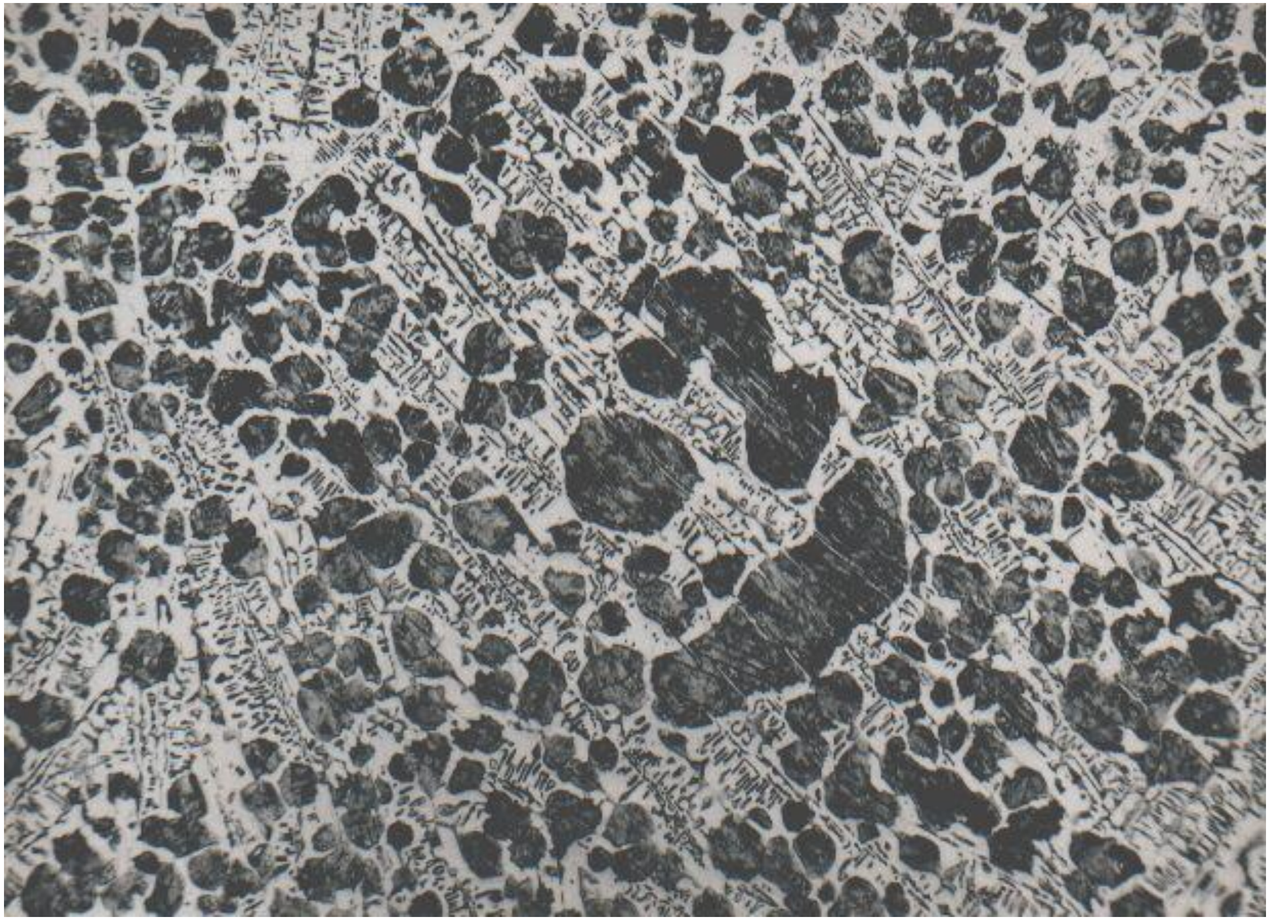


Ferrite + perlite + sulphides (steel)

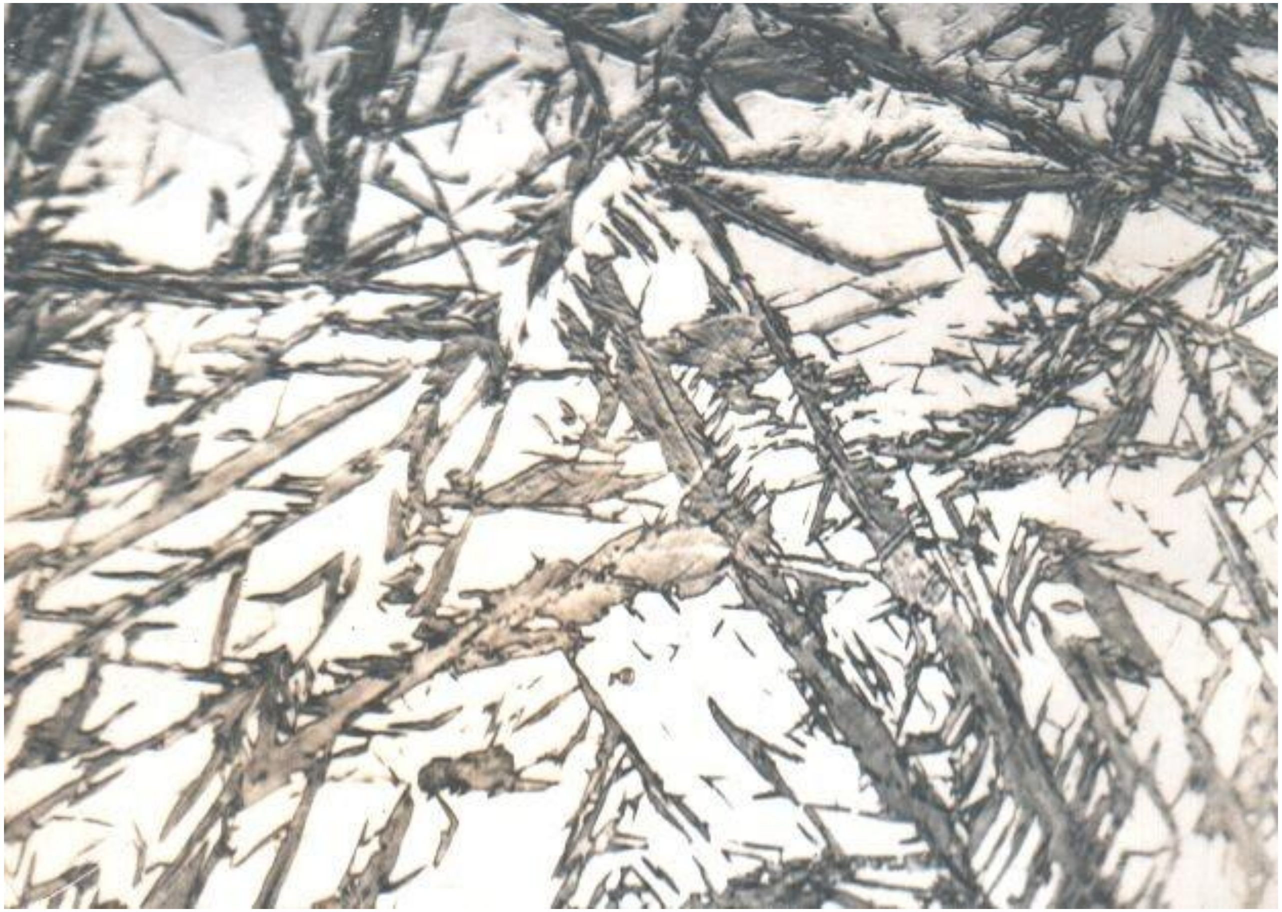


Ferrite + perlite (steel)

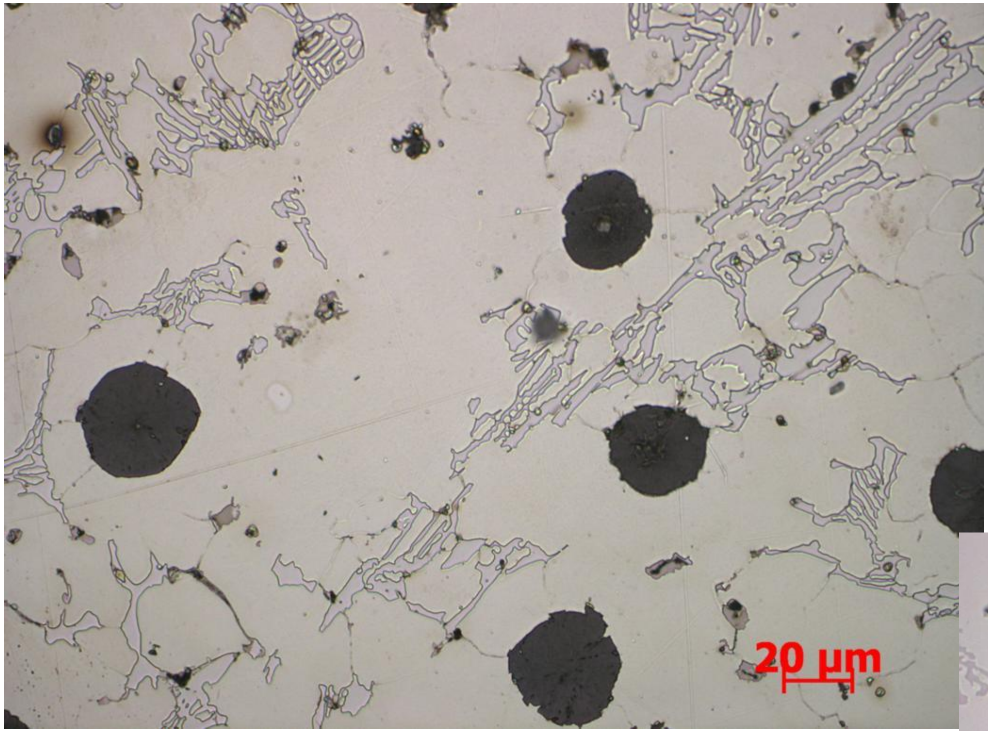
Perlite + little quantity of ferrite (steel)

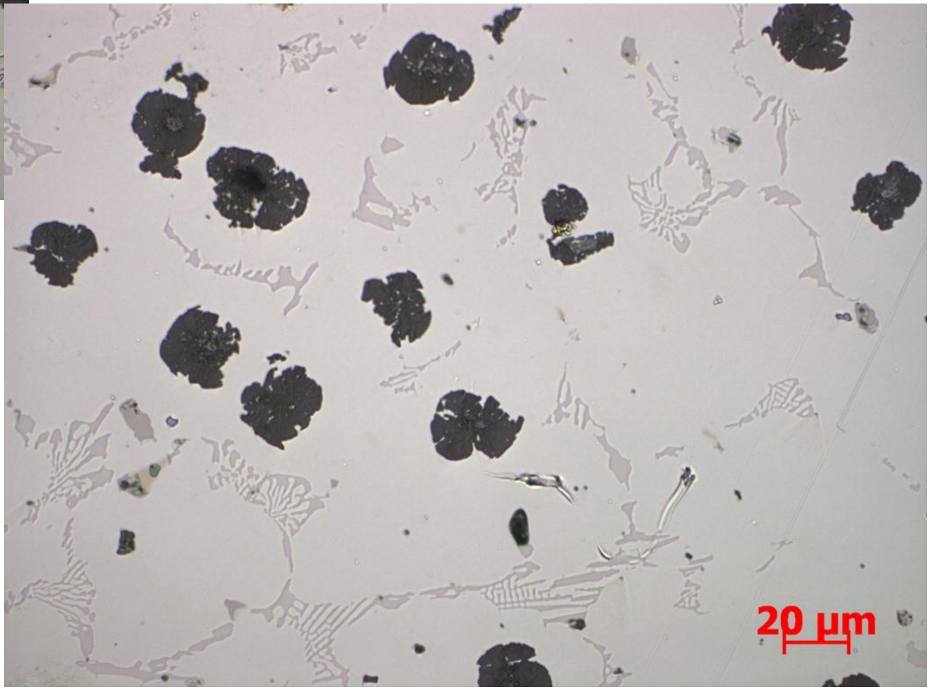


Ledeburite + perlite (steel)



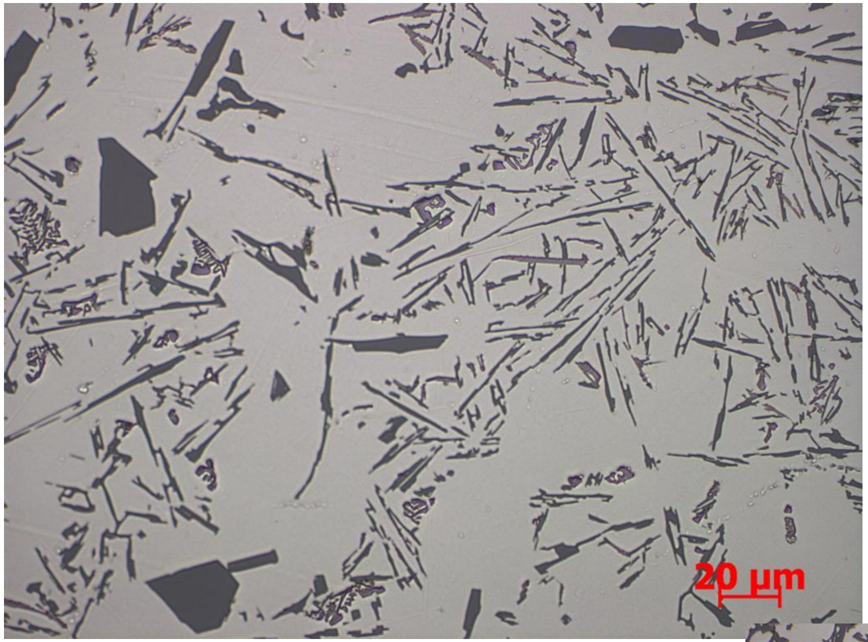
Martensite + austenite (steel)

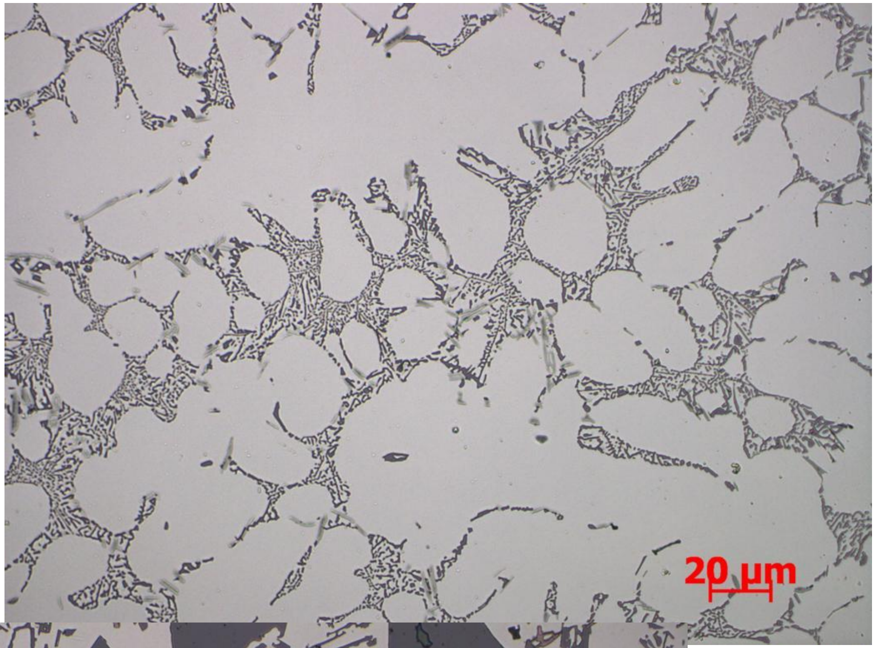


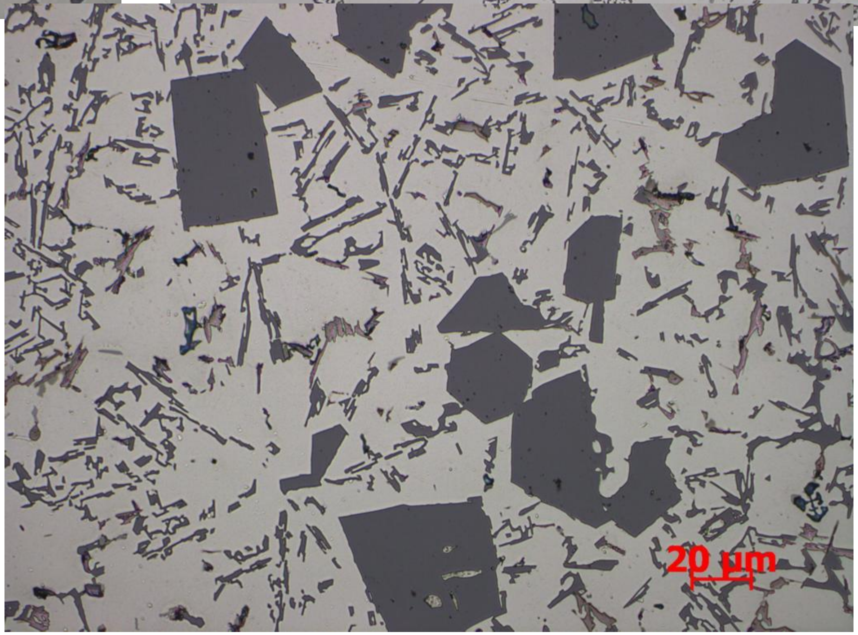


Graphite (ball) in cast iron

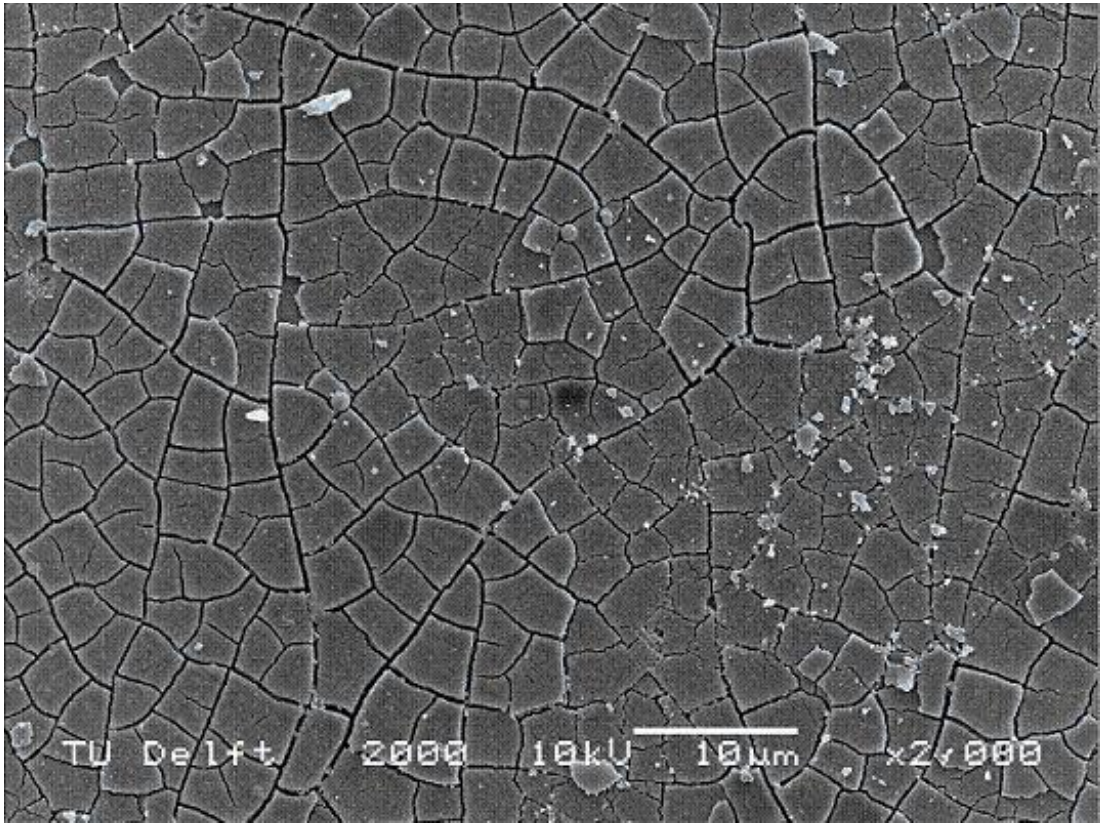
Graphite (plate) in grey cast iron



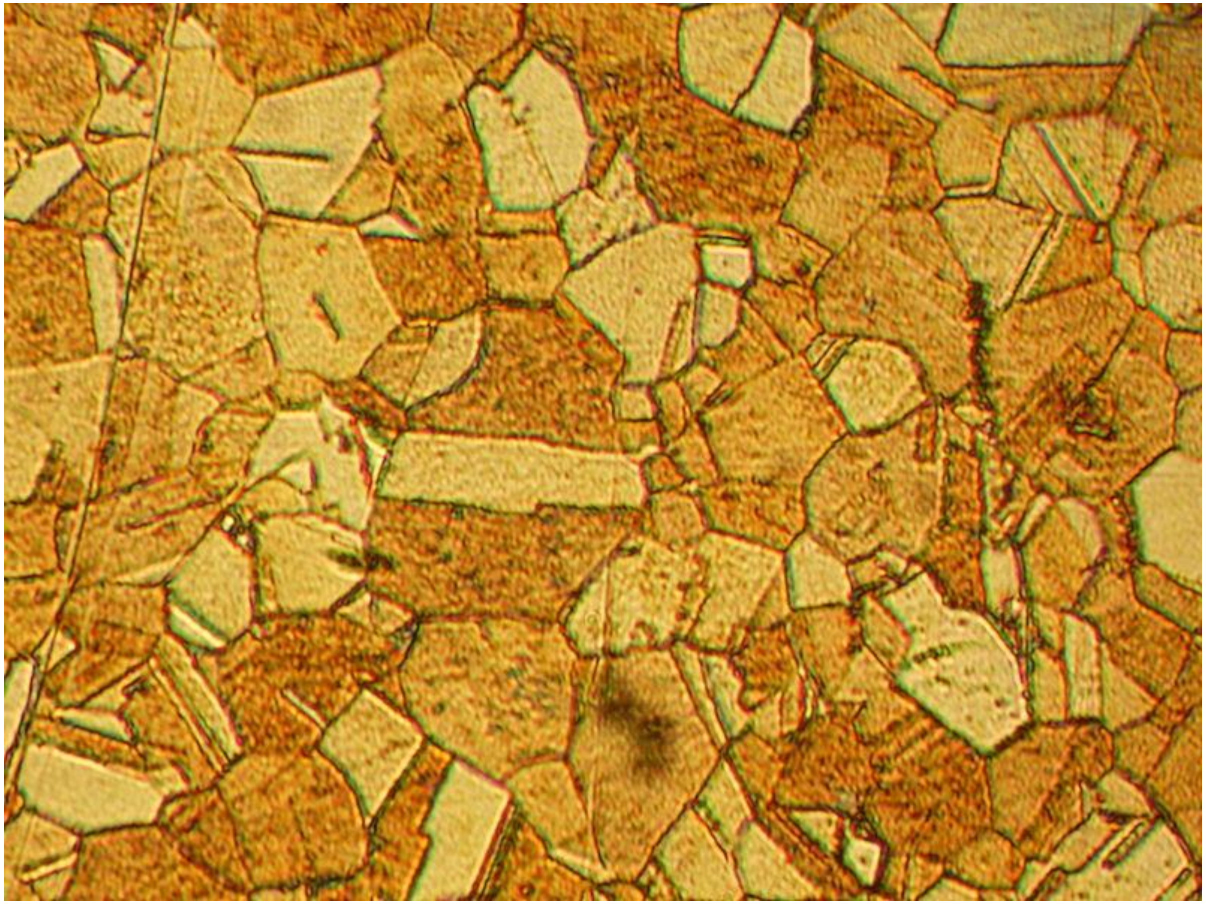




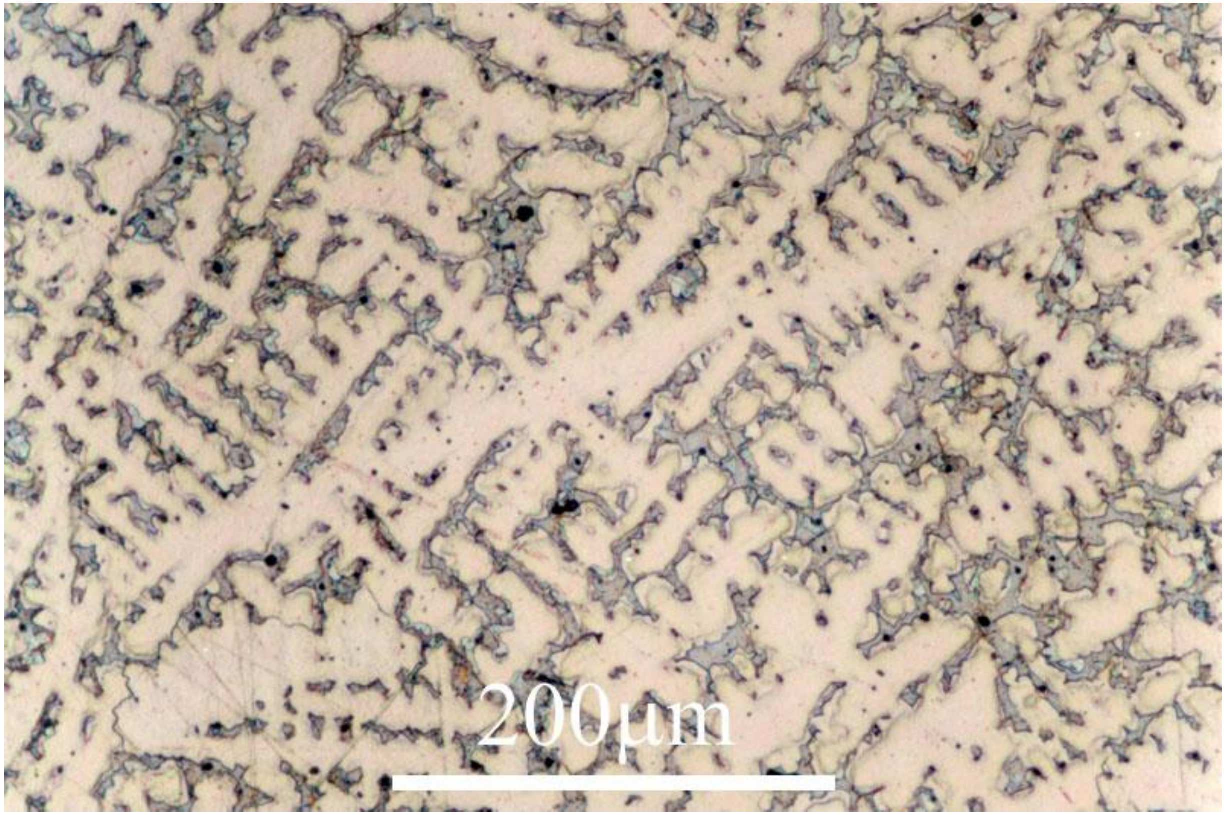
Aluminum



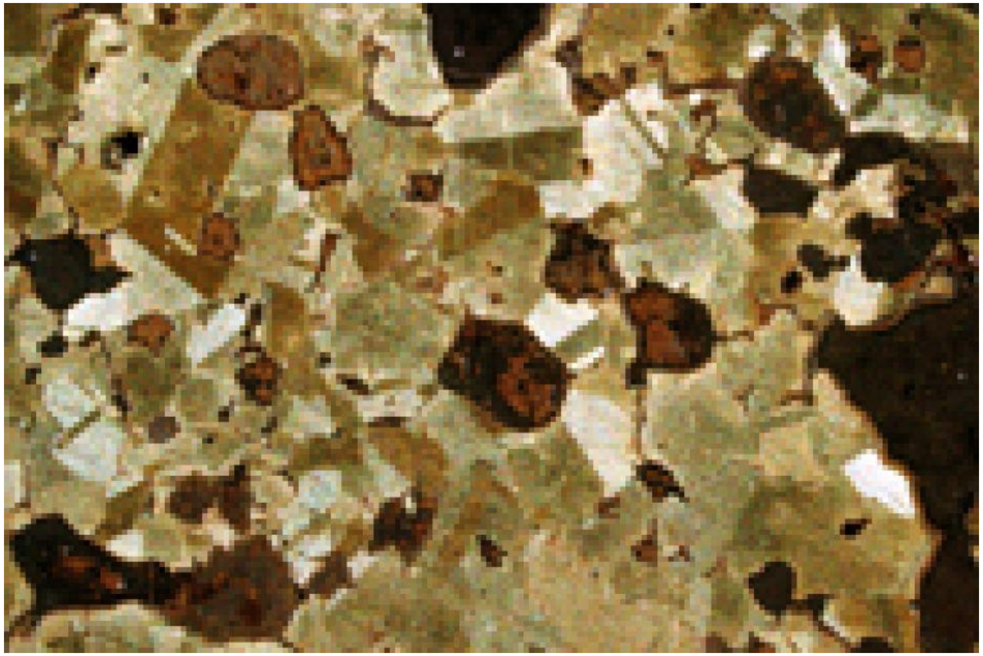
Zinc oxide



Brass



Copper



Gold

Thank you for attention

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