INTRODUCTION TO METALLIC MATERIALS FOR ORTHOPAEDICS

Physical metallurgy: Data

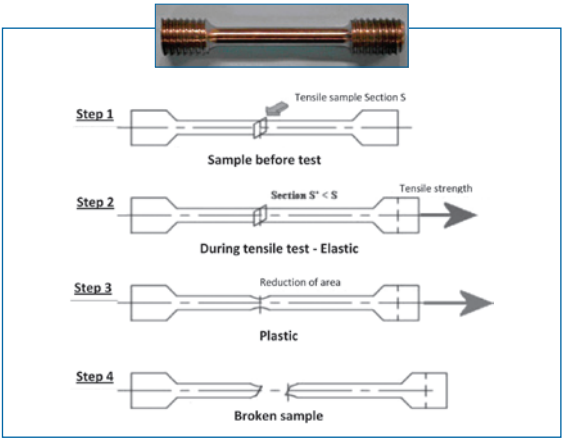
Tensile test

The principle is to apply on tensile test samples increasing elongation, and to measure the strength of the piece.

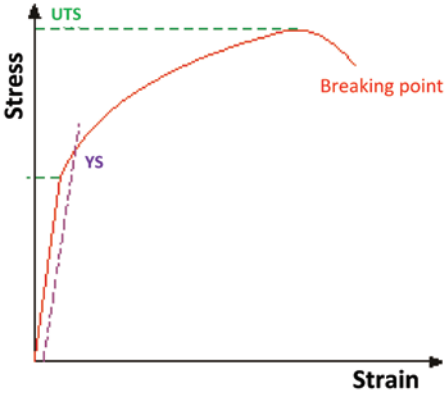
TEST SAMPLE : symetric form machined or not, flat or cylindrical, to ASTM and ISO specification.

Test conducted on tensile test machine capable of creating elongation and measuring strength.

TEST SAMPLE



STRAIN STRESS CURVE

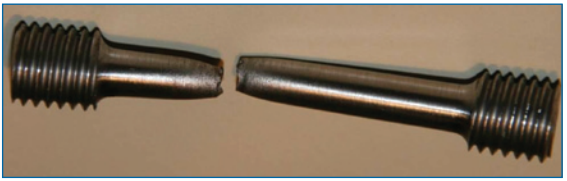


ELASTIC ZONE (FROM 0 TO YS)

- Small elongation : fraction of %.
- Elastic elongation : if the stress stops, the sample comes back to its initial length.
- Yield strength : when permanent elongation reaches a value of 0.2%.
- YS = F/So in N/mm² or MPa : same value.
- Longitudinal modulus : ratio of stress/elongation – depends on metals.
- Transverse modulus : ratio of elongation/reduction of section – unchanging for all metals ~ 0.3.

PLASTIC ZONE (FROM YS TO UTS)

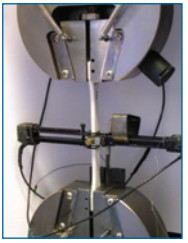
- Very important elongation : several %, up to 50/60%, for common metals.
- No elastic elongation : if the stress stops, the sample keeps a permanent strain.
- Breaking force : ultimate tensile strength (UTS) recorded,
- UTS = Fm/So in N/mm² or MPa.
- Strain grows as the test goes on, due to cold-working effect.



AFTER BREAKAGE

- Measurement of total length provides the % of elongation.
- E % = (Lu – L0) / L0 x 100.
- with L0 = Final length,
  L0 = Initial length.

YOUNGS MODULUS - IMPORTANT PARAMETERS



- Elasticity modulus E, in N/mm²: used in design.
- Yield strength YS 0.2 in N/mm²: MPa, used in RDM.
- Transverse modulus: poisson Coefficient : always around 0.3, used in RDM.
- Breaking force, UTS in N/mm², MPa: except particular cases.
- Breaking elongation E %: information on ductility: E < 5% is fragile (brittle).
- Standards: NF EN 10 002 and ASTM E8: difference about the measure of elongation (L0).

Hardness test

Resistance against penetration.

- Three types of tests
  -> Brinell,
  -> Rockwell,
  -> Vickers.
- Provides a rough estimate, usually nondestructive and cheap for mechanical strength.

BRINELL HARDNESS **FIGURE 1**

- HB.
- Usually a 10 mm ball, in steel HBS or carbide HBW, under 3000 kg.
- Measurement of circular print diameter, with a magnifying glass.
- Mechanical or metallurgical job shops for soft metal with low strength.
- Does not need prepared surface for accuracy.
- Standard: ASTM E10 - NF EN ISO 6506.

ROCKWELL HARDNESS **FIGURE 2**

- Usually in HRc, diamond cone, under 150 kg.
- Measurement of penetration between a pre-pressure of 15 kg.
- and the total pressure (15+135).
- High hardness typically hardened steels.
- Measure after heat treatment.
- Needs a surface preparation, typically ground.
- Standard: ASTM E18 - NF EN ISO 6508.

VICKERS HARDNESS **FIGURE 3**

- HV.
- Diamond square based pyramid.
- Variable pressure :
- Load ≥ 5 kg expressed in XXX HV 5.
- 0.2 kg ≤ F ≤ 5 kg, hardness under reduced pressure, expressed in XXX HV 0.2/5.
- 0.01 kg≤ F ≤ 0.2 kg micro hardness, expressed in XXX HV 0.01/ 0.2.
- Measurement of the diagonals of the print under microscope.

FIGURE 1

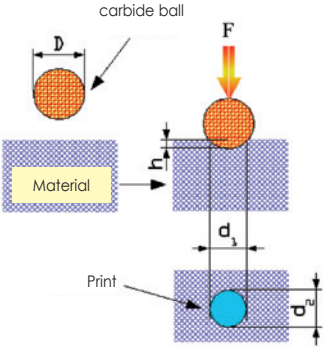


FIGURE 2

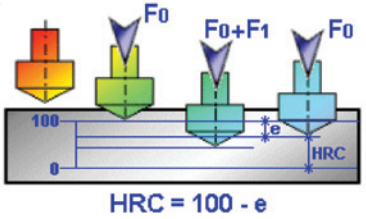
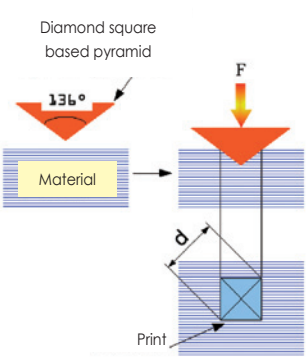


FIGURE 3



- Hardness on a corresponding table depends on the length of the print and the pressure.
- Test conducting in laboratory requires a mirror polished surface.
- Independent from metal.
- Micro hardnesses are usually used in R&D to identify the hardness of metallographic components.
- Standard : ASTM E92 - NF EN ISO 6507.

CORRESPONDING TABLES HARDNESS/UTS

- Unalloyed steels measure only.
- Increasing uncertainty for alloy steels, stainless and other metallic materials.
- Provides an immediate, rough estimate of UTS.
- Warning : use only if aware of uncertainty.
- Warning : material certificates should include UTS, YS, E%: hardness test cannot be used as substitute.
- UTS : 1KSi = 6.9 MPa.

HV Hardness	HB Hardness	HRB Hardness	HRC Hardness	(MPa) U.T.S.
115	109	65	-	390
120	114	67	-	410
125	119	69	-	420
130	124	71	-	440
135	128	73	-	450
140	133	75	-	470
145	138	77	-	480
150	143	79	-	500
155	147	81	-	510
160	152	82	-	530
165	157	84	-	540
170	162	85	-	550
175	166	86	-	570
180	171	87	-	580
185	176	89	-	600
190	181	90	-	610
195	185	91	-	630
200	190	92	-	650
205	195	93	-	660
210	200	94	-	680
215	204	95	-	690
220	209	96	-	710
225	214	96	-	720
230	219	-	-	740
235	223	-	-	750
240	228	-	20	770
245	233	-	21	780
250	236	-	22	800
255	242	-	23	820
260	247	-	24	830
265	252	-	25	850
270	257	-	27	860
275	261	-	26	880
280	266	-	27	890
285	271	-	28	910
290	276	-	29	930
295	280	-	29	940
300	285	-	30	960
310	295	-	31	990
320	304	-	32	1020
330	314	-	33	1060
340	323	-	34	1090

HV Hardness	HB Hardness	HRB Hardness	HRC Hardness	(MPa) U.T.S.
350	333	-	36	1120
360	342	-	37	1160
370	352	-	38	1190
380	361	-	39	1220
390	371	-	40	1260
400	380	-	41	1290
410	390	-	42	1330
420	399	-	43	1360
430	409	-	44	1400
440	418	-	45	1430
450	423	-	45	1470
460	432	-	46	1500
470	442	-	47	1540
480	450	-	48	1570
490	456	-	48	1610
500	466	-	49	1650
510	475	-	50	1680
520	483	-	51	1720
530	492	-	51	1760
540	500	-	52	1790
550	509	-	52	1830
560	517	-	53	1870
570	526	-	54	1910
580	535	-	54	1940
590	543	-	55	1980
600	552	-	55	2020
610	560	-	56	2060
620	569	-	56	2100
630	577	-	57	2140
640	586	-	57	2180
650	-	-	58	2220
660	-	-	58	-
670	-	-	59	-
680	-	-	59	-
690	-	-	60	-
700	-	-	60	-
720	-	-	61	-
740	-	-	62	-
760	-	-	63	-
780	-	-	63	-
800	-	-	64	-
820	-	-	65	-
840	-	-	65	-

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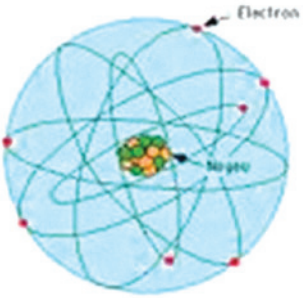
Metallography

Overview : Nuclear structure of materials

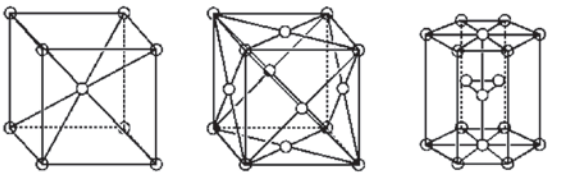


ATOM

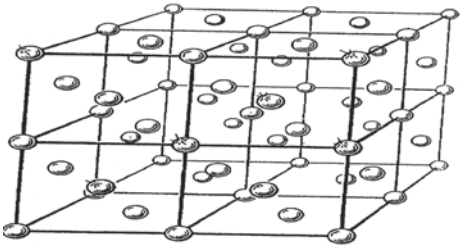
- Negative electron, very low mass, on orbital.
- Nucleous positive proton and neutron neutral.
- Nucleous : most of the mass.

CRYSTALS

- Metals are crystals.
- Crystals are organised according to defined geometric position, infinitely repeated.
- 90 % of metals have such crystals.



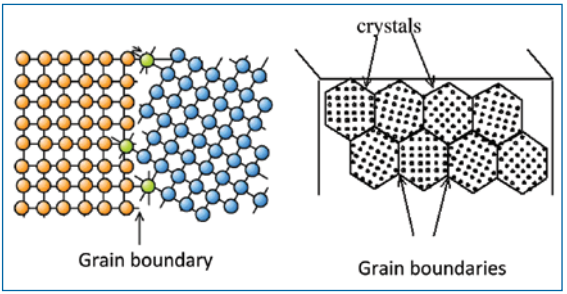
Body Centered Cubic - BCC | Face Centered Cubic - FCC | Hexagonal Closed Packing - HCP



Parallel atomic plan

Wrap up

- Metal made up of parallel atomic plans.
- Strain under YS : small movement of atoms around their balance position.
- Strain above YS : sliding of plans while recovering crystal symmetry.
- From slidings to slidings : further plastic elongation including cold-work.
- Grain are billions of crystals.
- Limited dimensioned crystals : hundredth mm grains.
- Grain visible at the optical microscope, magnification x 100, after mirror polishing and a slight chemical etching.
- Grain boundaries : disrupted crystallization area, preferred zone of impurities.



GRAIN SIZE MEASUREMENT

- Comparing typical pictures, easiest and most widely used.
- Counting of grains on a given section.
- Average intercept of grain boundaries.

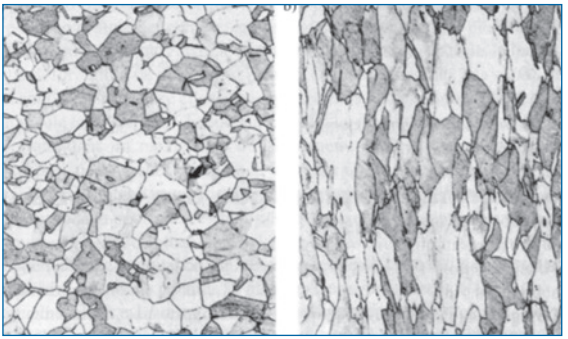
- Methods providing a value, or « average grain value ».
- The highest the number is, the finest the grain is.

IMPORTANCE OF THE GRAIN SIZE

- *Big grain* : small surface of grain boundary, high level of risk of brittleness, through intercrystalline dismantling, nonmetallic inclusions.
- *Fine grain* : high surface of grain boundary, low risk of brittleness.

COLD-WORK EFFECT

- Default of atomic structure.
- Cold worked metal.
- Elongated grain size.
- To come back to original condition, need energy by heating "annealing".
- Germination and new grain growth.



a) b)

Overview on steels

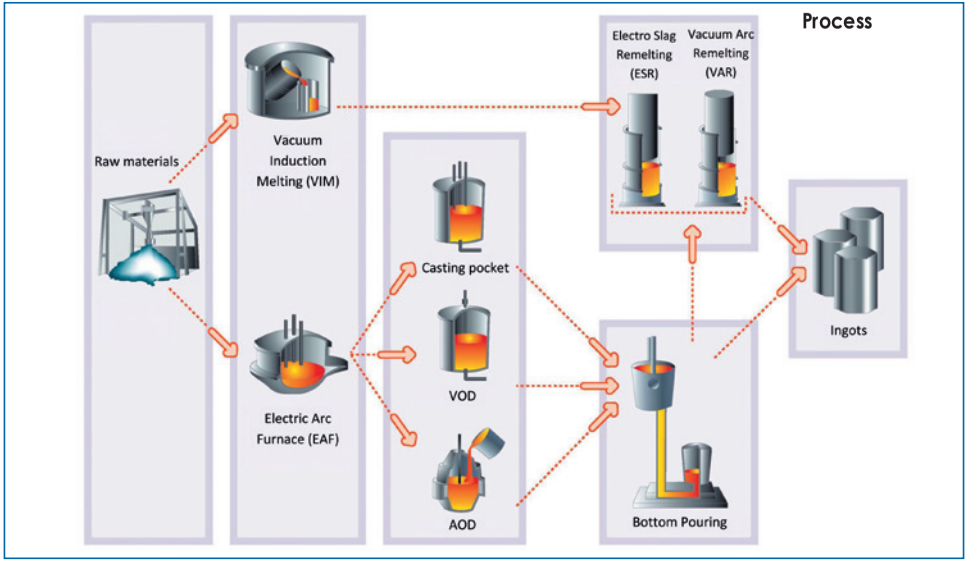
STEEL: iron base with low percentage of carbon

Phases include ferrite, austenite, cementite and martensite, connected to structure and heat treatment conditions.

Stainless steels

- Stainless steels – Cr ≥ 12 %.
- Corrosion resistance gained a surface oxygen, moving towards a Cr oxide layer.
- Layer resistant to chemicals, continued and adhesive, protecting the metal.
- Known as « passivated ».
- C content the lowest as possible, with Cr23C6 carbide. and left Cr no more available for corrosion resistance.
- Process :
  - Electric Arc Furnace (EAF) of iron and ferro alloys,
  - C adjustment with AOD « Argon Oxygen Decarburisation » converter,
  - Second melt with VAR « Vacuum Arc Remelting » or ESR « Electro Slag Remelting », if needed, to reduce nonmetallic inclusions and improve steel homogeneity.

CREDIT: Aubert&Duval


Process
Raw materials
Vacuum Induction Melting (VIM)
Electric Arc Furnace (EAF)
Casting pocket
VOD
AOD
Electro Slag Remelting (ESR)
Vacuum Arc Remelting (VAR)
Bottom Pouring
Ingots

Metallic materials for Medical instruments

Stainless steels for medical instruments

- For the use in medical instrumentation, some standards have to be met F 899 (ASTM).
- On technical data sheets below, typical data are given.

Martensitic steels

- Used in hardened-tempered condition, in a martensitic metallurgical condition.

Martensitic precipitation hardening steels

- Hardening by precipitation of Copper or Titanium atomic structure.
- Precipitation hardening with tempering known as « aging » process.
- Delivered in a martensitic, hardened condition, aged at 480 °C, after machining.

Austenitic steels

- 18 % Cr + Ni ≥ 8 %.
- FCC structure (austenitic), independent from temperature and heat treatment.

Martensitic stainless steels to ASTM F899

DESIGNATION				CHEMICAL ANALYSIS						Δ HRC HARDENED TEMPERED AT 200 °C	APPLICATION	COMMENT
AISI/ UNS	Alphanumerical	Numerical	Common	C	Cr	Ni	Mo	V	N			
420A	X20Cr13	1.4021	/	0.20	13	/	/	/	/	43 HRc UTS 1450 N/mm², YS 1150 N/mm²	Cutting tools	Limited corrosion resistance
420B	X30Cr13	1.4028	X13	0.30	13	/	/	/	/	52 HRc UTS 1750 N/mm², YS 1500 N/mm²	Cutting tools	Limited corrosion resistance
420C	X46Cr13	1.4034	/	0.45	13	/	/	/	/	52HRc	General use Cutting tools	Limited corrosion resistance
420F	X30Cr13	1.4197	/	0.35	13	/	/	/	/	52HRc	Bar turning	Limited corrosion resistance

431	X15CrNi17.2	1.4057	APX	0.15	17	2	/	/	/	42 HRc	Small drills	Usual delivery (UTS ~ 1000 MPa)
440A	X70CrMo17	/	/	0.70	17	/	0.5	/	/	56 HRc	Cutting tools	Limited corrosion resistance
440B	X90CrMo17	1.4112	/	0.90	17	/	0.5	/	/	57 HRc	Cutting tools	Limited corrosion resistance
440C	X105CrMo17	1.4125	XDBD	1.0	17	/	/	/	/	60 HRc	Cutting tools	Limited corrosion resistance
420 Mod	X40CrMoVN15.2	1.4123	X15TN	0.4	15.5	/	2	0.3	0.2	59 HRc	Cutting tools	Very good corrosion resistance

X13, APX, XDBD, X15TN are registred trademarks from Aubert&Duval

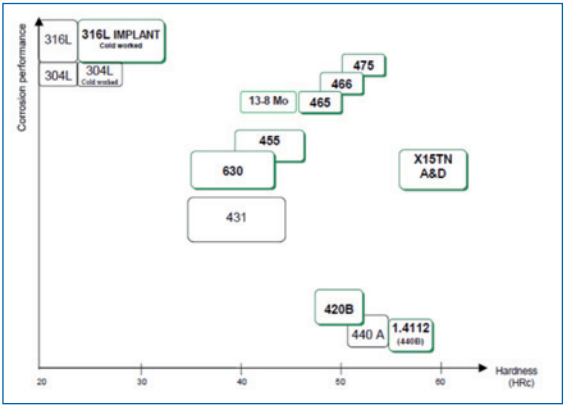
Precipitation hardening martensitic stainless steels to ASTM F899

DESIGNATION				CHEMICAL ANALYSIS					Δ AGED HRC	APPLICATION	COMMENT
AISI/ UNS	Alphanumerical	Numerical	Common	C	Cr	Ni	Mo	Others			
630	X5CrNiCuNb16.4	1.4542	Custom 630 DU3 17-4 PH	0.06	16.5	4	/	Cu 4 Nb+Ta 0.3	43 HRc UTS 1350 N/mm² YS 1200 N/mm²	Non cutting instruments, rasp	Heat treated forgiving different simple using lab
XM16	X2CrNiCuTiNb12.9	1.4543	Custom 455 MX455	0.02	12	8.5	/	Cu 2 Ti 1.2 Nb+Ta 0.3	48 HRc UTS 1600 N/mm² YS 1500 N/mm²	Drivers, PVD control drills	Torque instruments
S 11100	X2CrNiMoAlTi12.11.2	/	MX466	0.02	12	11	2	Al 1.5 Ti 0.3	49 HRc UTS 1650 N/mm² YS 1510 N/mm²	Drivers, drills, taps guides	High end quality
S 46500	X2CrNiMoTi12.11.1	/	Custom 465	0.02	12	11	1	Ti 1.5	49 HRc UTS 1650 N/mm² YS 1510 N/mm²	Drivers, drills, taps guides	Cold worked improves aged HRC
S13800	X5CrNiMoAl13.8.2	/	PH13.8Mo	0.03	12.5	8	2.25	Al 1.5	46 HRc UTS 1550 N/mm² YS 1450 N/mm²	Drivers, drills, taps guides	Torque
S47500	X1CrCoNi-MoAl11.8.8.5	/	Custom 475	0.01	11	8	5	Co 8.5 Al 1.25	UTS 2100 N/mm² YS 2000 N/mm²	Drivers, drills, taps guides	Cold worked improves aged HRC

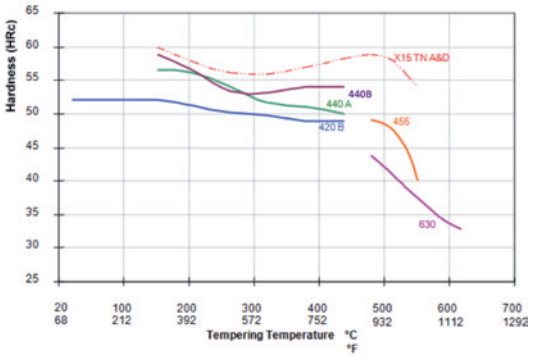
Custom 630, 455, 465, 475 are registred trademarks from Carpenter Technology
17-4 PH, PH13.8Mo are registred trademarks from Armco Inc
DU3, MX455, MX466 are registred trademarks from Aubert&Duval

Austenitic stainless steels to ASTM F899

DESIGNATION				CHEMICAL ANALYSIS				MECHANICAL PROPERTIES – RM N/MM²		APPLICATION	COMMENT
AISI/ UNS	Alphanumerical	Numerical	Common	C	Cr	Ni	Mo	Annealed	Cold-work level		
301	X10CrNi18.8	1.4310	301	0.10	17	7	/	UTS 600N/mm² YS 200 N/mm²	2000	Non cutting guides, bushings	Cold worked version with 900 to 1200 N/mm²
304	X5CrNi18.8	1.4301	304	0.05	18	10	/	UTS 600N/mm² YS 200 N/mm²	1500	Non cutting guides, bushings	Cold worked version with 900 to 1200 N/mm²
304L	X2CrNi18.10	1.4306	304L	0.02	18	10	/	UTS 600N/mm² YS 200 N/mm²	1500	Non cutting guides, bushings	
316	X5CrNiMo17.12.2	1.4401	316	0.05	18	12	2	UTS 600N/mm² YS 200 N/mm²	1500	Non cutting guides, bushings	Cold worked version with 900 to 1200 N/mm²
316L	X2CrNiMo17.12.2	1.4436	316L	0.02	18	12	2	UTS 600N/mm² YS 200 N/mm²	1500	Non cutting guides, bushings	



Comparative Hardness performance



- Martensitic stainless steels: Hardening is obtained by 1040°C Air or Oil quenching followed by tempering at θ < 420°C (θ < 788° F).
- Precipitation hardening (PH) stainless steels: Hardening is obtained by an aging treatment on the as supplied condition. Parameters are specific for each alloy.
- Indicated mean values are obtained from tests.

Metals for implants

Implantable metals

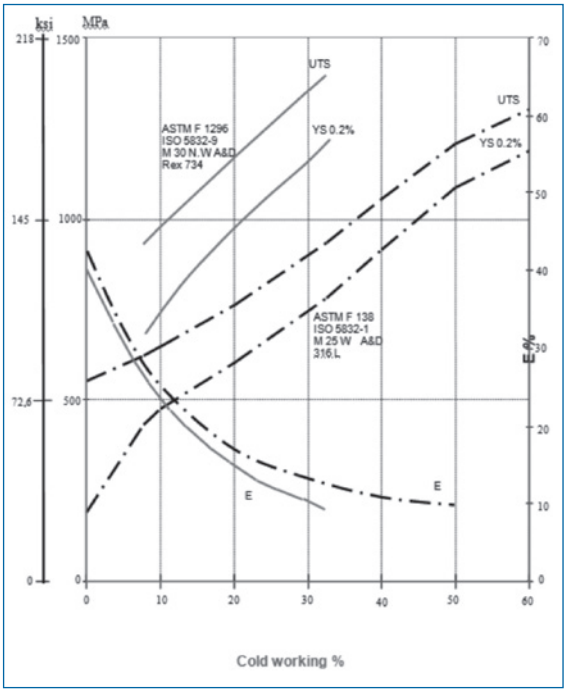
- Must meet standards for permanent implants in humans, usually ISO and ASTM.
- Stainless steels : melting and consumable electrode second melt, for :
  - Very low rate of tramp elements, such as sulfur,
  - Very low rate of nonmetallic inclusions,
  - Reduction of segregations.
- For Cobalt base, primary melting under 'Vacuum Induction Melting' – VIM, then second melt ESR.
- For Titanium base, double melt VAR.
- On technical data sheets below, typical data are given.

CREDIT: Aubert&Duval – VAR/ESR Remelting oven

Implantable austenitic stainless steels

DESIGNATION				CHEMICAL ANALYSIS						UTS – N/MM²		APPLICATION	COMMENT
ISO	ASTM	Alphanumerical	Common	C	Cr	Ni	Mo	Mn	Others	Annealed	Cold-work level		
5832-1	F138	X2CrNiMo18.14.3	Biodur 316LS M25W	0.02	18	14	3	/	/	600	900/1400	Traumatology	Basic grade
/	F1314	X2CrNiM22.13.5	22.13.5 M28NW	0.03	21	12	2.5	5	Nb 0.2 – N 0.3 – V 0.2	700	1100	Articular implants	Not very used
5832-9	F1586	X2CrNiMnMoN21.9.4	Rex734 Biodur 734 M30NW	0.05	21	9	2.5	4	Nb 0.3 – N 0.4	800	1200	Articular implants	High strength
/	F2229	X8MnCrMoN23.21.1	Biodur 108 NONICM2	0.06	21	/	0.7	23	N 0.9	900	1400	External spinal fixative	Analergic

Biodur 316LS, Biodur 108, Biodur 734, 22.13.5 are registred trademarks from Carpenter Technology
M25W, M28NW, M30NW, NONICM2 are registred trademarks from Aubert&Duval



Cobalt base alloys

- Cobalt instead of iron as base.
- Cobalt element non-resistant to corrosion : need of chromium, to produce a passive layer, resistance to corrosion and biocompatibility.
- Molybdenum to increase pitting corrosion resistance.

Cobalt base alloys

DESIGNATION			CHEMICAL ANALYSIS					CONDITION				APPLICATION	COMMENT
ISO	ASTM	Common	C	Cr	Ni	Mo	Co	Annealed	Hot worked	Warm worked	Cold worked+ Age		
5832-12	F1537	M64 BC	≤ 0.15	28	≤ 1	6	Balance	UTS 1000 N/mm² YS 600 N/mm²	UTS 1100 N/mm² YS 800 N/mm²	UTS 1250 N/mm² YS 900 N/mm²		THR TKR	Low carbon
5832-12	F1537	M64 C	0.16 / 0.30	28	≤ 1	6	Balance	UTS 1000 N/mm² YS 600 N/mm²	UTS 1100 N/mm² YS 800 N/mm²	UTS 1250 N/mm² YS 900 N/mm²		THR TKR	High carbon
5832-7	F1058	Phynox	0.02	20	35	10	Balance	UTS 950 N/mm² YS 450 N/mm²	/	/	UTS 1600 N/mm² YS 1500 N/mm² E% 15	Wire	

M64C, M64BC are registred trademarks from Aubert&Duval
Phynox is a registred trademark from Aperam alloys Imphy

Titanium and its alloys

From ore, obtention of titanium metal, by a chemical way, into a powder (Kroll process):

- Cold pressing of powder to obtain 'titanium sponge'.
- Melting 'Vacuum Arc Remelting' – VAR – of sponges, to obtain an ingot.
- Minimum of two successive VAR remelt, to obtain a high degree of purity required for the medical grade.
- Light metal, with mass about half of steel or cobalt alloys.
- Modulus lower than the one of stainless steels or cobalt alloys, closer to that of bone.
- On surface, very stable passive TiO_2 layer ; very high corrosion resistant with high biocompatibility.

CREDIT : Aubert&Duval

DESIGNATION			CHEMICAL ANALYSIS							UTS – N/MM²	YS – N/MM²	APPLICATION	COMMENT
ISO	ASTM	Common	N	C	H	Fe	O	Others	Ti				
5832-2	F67	CP Grade2 T40 TIMETAL® 50A	≤ 0.03	≤ 0.08	≤ 0.0125	≤ 0.2	≤ 0.25	/	balance	355	300	Dental implants CMF and screws	low mechanical constraints and appreciated flexibility deformability
5832-3	F136	Ti-6Al4V TIMETAL® 6-4ELI Grade 23	≤ 0.05	≤ 0.08	≤ 0.012	≤ 0.25	≤ 0.13	Al 6 V 4	balance	900	800	Reconstruction : THR, shoulder Trauma : screws, nails, plates, spinal	high purity for maximum biocompatibility Higher strength alloys than grade 2
5832-3	F1472	Ti-6Al4V non ELI Grade 5 TIMETAL® 6-4	≤ 0.05	≤ 0.08	≤ 0.012	0.3	0.2	Al 6 V 4	balance	930	830	Reconstruction : THR, shoulder Trauma : screws, nails, plates, spinal	10% increased strength
5832-11	F1295	Ti-6Al7Nb	≤ 0.05	≤ 0.08	≤ 0.009	≤ 0.25	≤ 0.20	Ta ≤ 0.5 Al 6 Nb 7	balance	1000	900		Same strength as Ti6Al4V ELI
5832-14		Ti-15 Mo5 Zr 3Al	≤ 0.05	≤ 0.08	≤ 0.02	≤ 0.30	≤ 0.20	Mo 15 Zr 5 Al 3	balance	1000	900		

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Young's modulus – Comparison table