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Behavior of materials used in design of highly stressed engineering components at different temperatures

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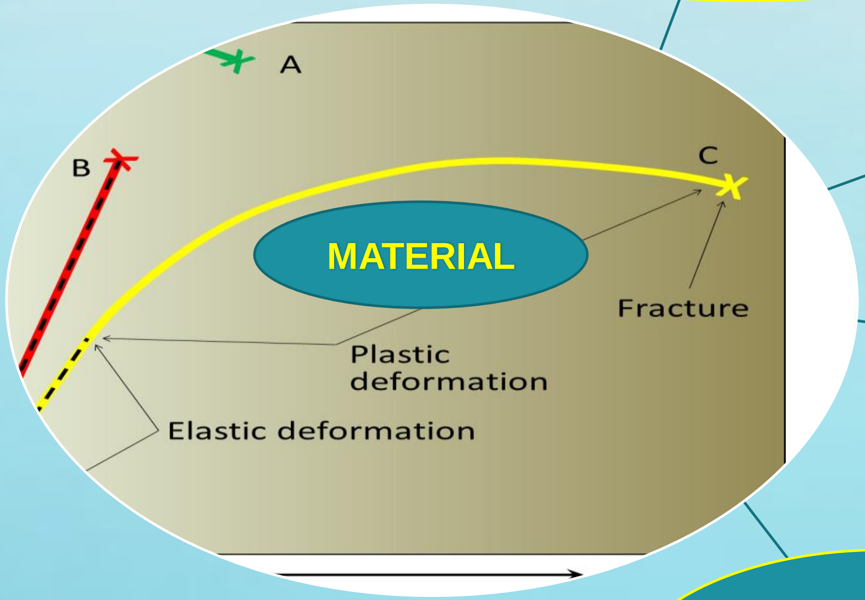
Considerations contained in the lecture:

1. **Mechanical responses** of materials in service life: stresses, strains, modulus of elasticity, fracture impact energy, creep, fatigue strength (fatigue limit).

2. **Temperature dependence** of mechanical properties

σ_m- Ultimate tensile strength
$\sigma_{0.2}$- Yield strength
E – Modulus of elasticity
K_{Ic}- Fracture toughness
σ_f- Fatigue limit



3. **Considered (tested) materials: 50CrMo4** (1.7228 /AISI 4150); **42CrMo4** (1.7225, AISI 4140); **30CrNiMo8** (1.6580 /AISI 4340); **18CrNi8** (1.5920); **20MnCr5** (1.7147, AISI 5120); **51CrV4** (1.8159 / AISI 6150).

4. **Highly dynamically stressed components (gears, crankshaft, etc)**

Introduction-preliminary considerations

Particular materialis used in defined environmental conditions. This means that material has to be chosen in accordance with the purpose of the structure, with the working / operating coditions, with the choice of the process by which it is to be shaped or joined. Under structure, it is understood any type of construction or machine. Namely, every machine is a construction but every construction is not a machine. In the considered case, such as highly stressed conditions, used material must be able to take high stresses, dynamic loads, and must be creep resistant. Based on such requirements, it is suggested, that material can be exposed to high stresses, high temperatures, creep and fatigue. Regarding the quality and reliability of the structure, taking into consideration the entire structure life from design through manufacture and exploitation, several key problems must be analysed. These problems are: purpose for which structure is intended to be used, working / operating conditions, choice of material, lifetime prediction, safety, common causes of failures, possible (common) failure modes, analyses of how and why structural component has failed, etc. Causes of the failures and appropriate failure modes are interconnected. In engineering practice, structure is usually designed and manufactured in order to guarantee that it does not contain any failure, although this does not have to be the correct enough. As common causes of failures can be mentioned: inadequate choose of material, design errors (used material, the size and shape of an engineering component, properties), manufacturing defects, structural loading, temperature effects, misuse (the structure is subjected to conditions for which it was not designed), assembly errors, improper maintenance, unforeseen operating conditions, inadequate control, etc. These causes, generally, may be divided into pre-existing causes and that appearing in service life. The same applies to failure modes. Commonly observed failures mode in engineering practice are: yielding, creep, fatigue, wear, corrosion, impact, buckling, etc. Any of particular mechanical failure has its cause of origin and the form of expression (mode of representation), i.e., failure mode**. In this sense the cause can provide the answer why an engineering component has failed while the failure mode enables the answer how an engineering component has failed. In accordance with the considered problems in this topic ,i.e., design of highly stressed engineering components**, the following subjects related to the applied materials were explored and analysed: **mechanical properties, creep and fatigue of material**. Designer who deals with material selection must be familiar with all of mentioned subjects. Some details of investigated responses of considered materials can be found in the literature. Several materials were selected for testing with respect to their use in high-stressed engineering elements, as mentioned above.

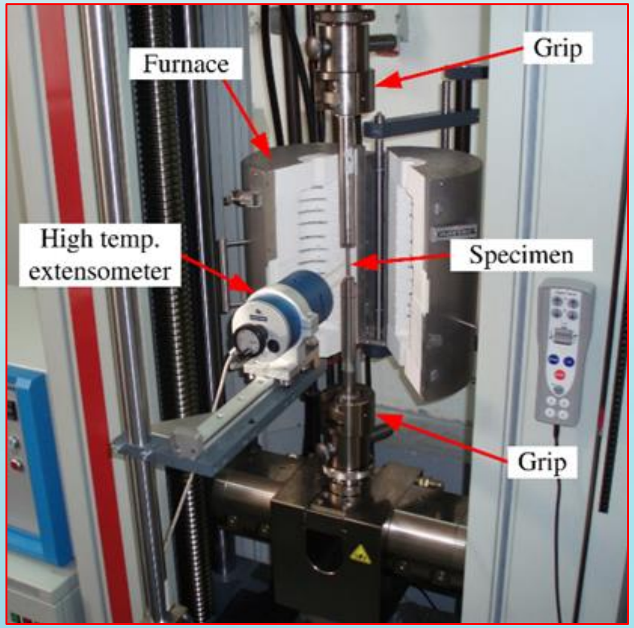
Investigated materials

Material / round bar (mm)	Chemical composition (some elements only) mass (%)						As - received
	C	Cr	Si	Ni	Mn	Mo	
30CrNiMo8 (**1.6580** / AISI 4340) / 20	0.29	2.07	0.31	1.89	0.41	0.24	annealed
20MnCr5 (**1.7147** / AISI 5120) /18	0.22	1.11	0.29	0.08	1.23	0.01	annealed
51CrV4 (**1.8159** / AISI 6150) /20	0.45	1.09	0.32	0.22	0.92	0.005	Soft annealed-cold drawn
42CrMo4 (**1.7225** / AISI 4140) / 16	0.42	1.07	0.24	-	0.84	0.22	Soft annealed-cold drawn
50CrMo4 (**1.7228** / AISI 4150) / 20	0.487	0.999	0.257	-	0.735	0.185	-
18CrNi8 (**1.5920**) / 20	0.19	1.8	0.24	1.8	0.48	0.091	annealed

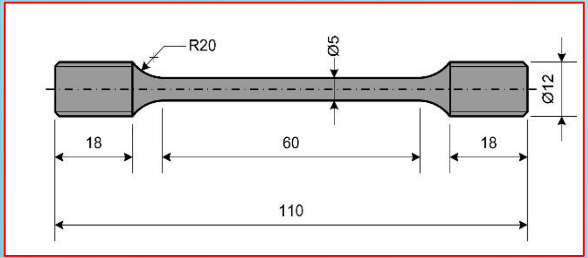
Consideration in relation to:	**Material behavior requirements**
Mechanical properties (σ_m; $\sigma_{0.2}$; E)	Higher level for any purpose
Creep	Greater resistance to creep
Fatigue	greater resistance to fatigue - greater fatigue limit

Experiments - used equipment and specimens

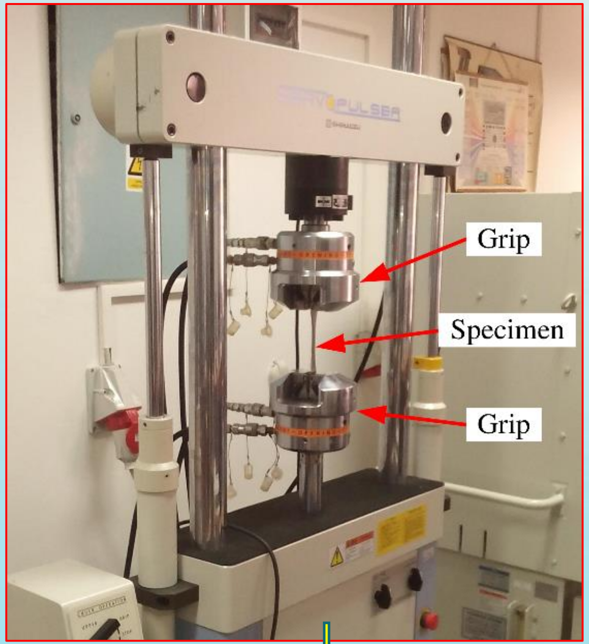
Basic testing machine



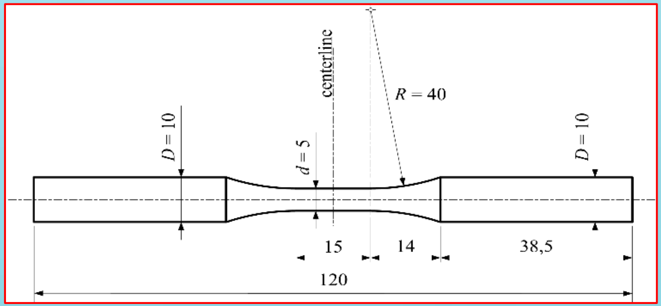
specimen



Dynamic testing machine

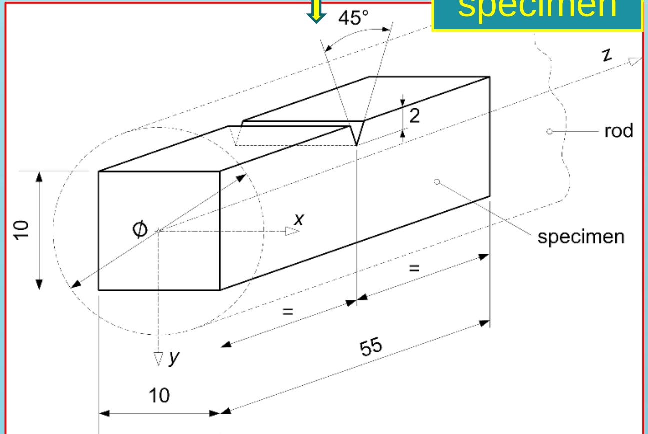


specimen



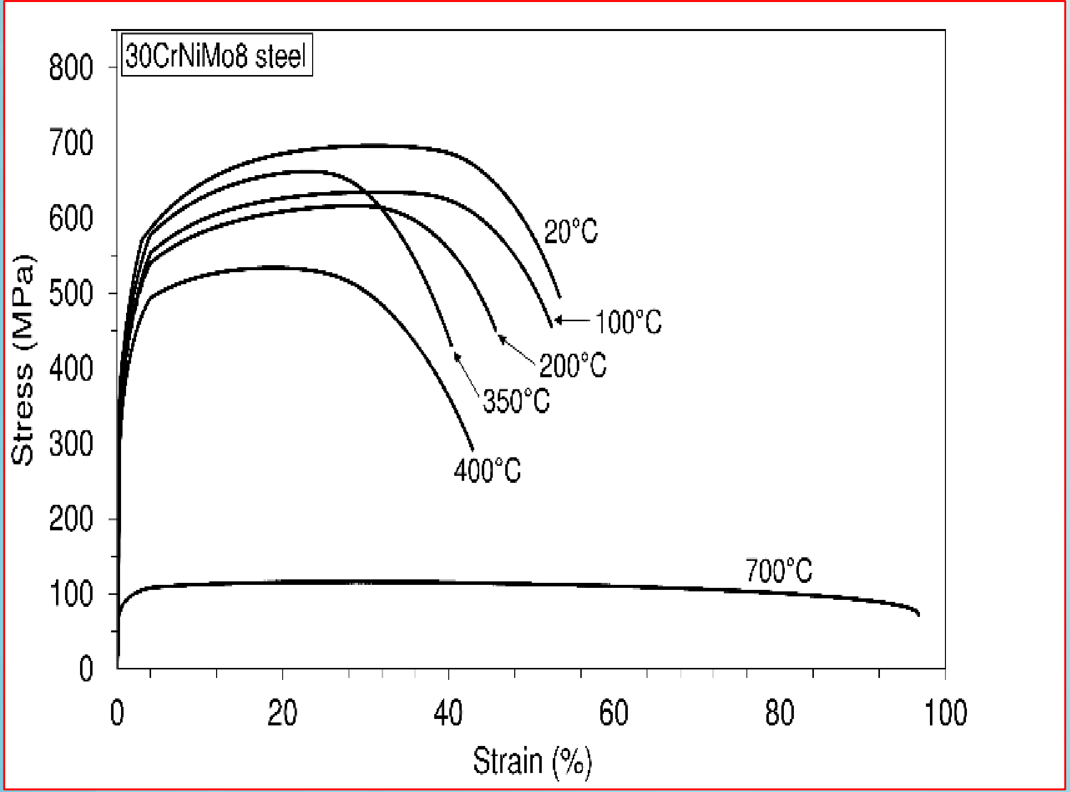
Charpy impact machine

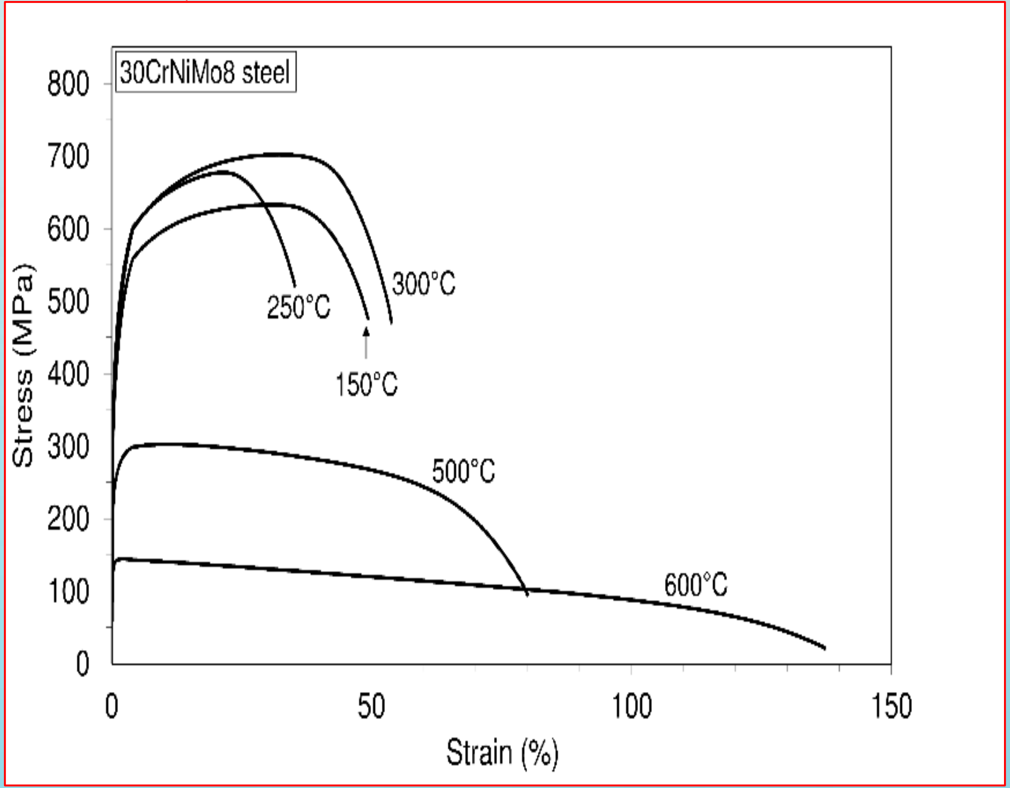
specimen



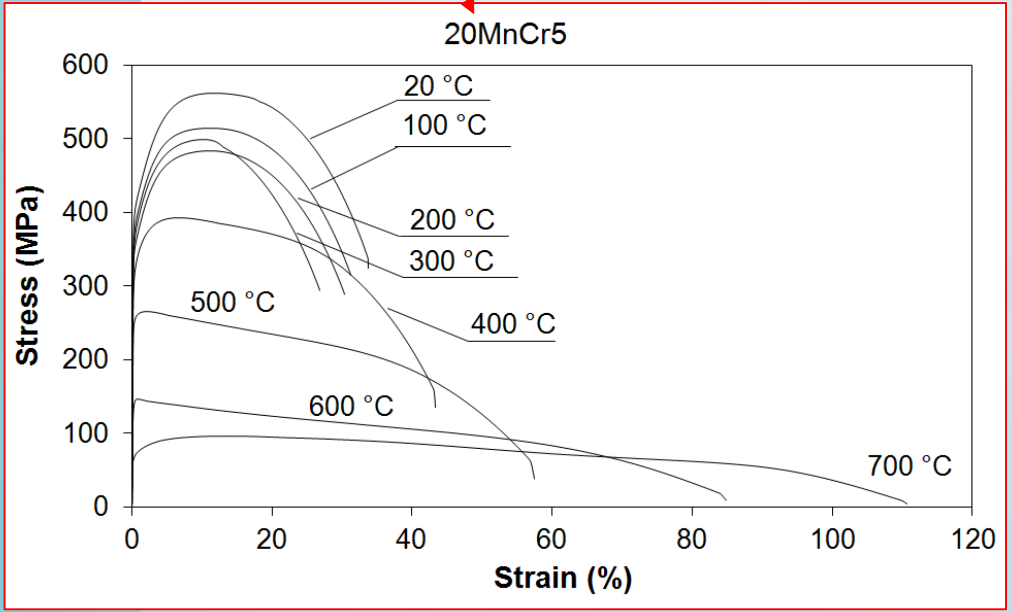
Mechanical responses - mechanical properties
$\sigma - \varepsilon$

30CrNiMo8

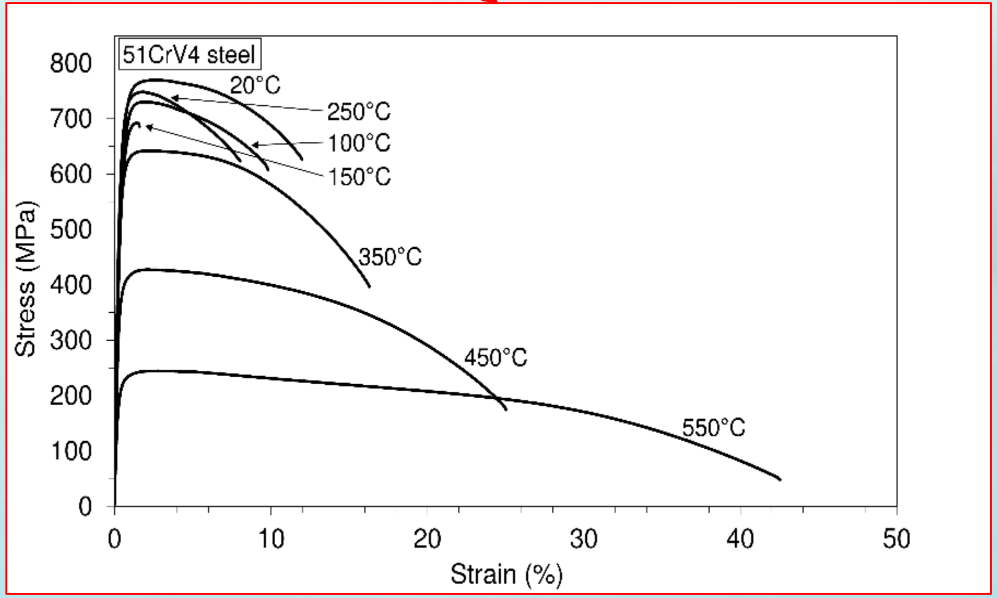




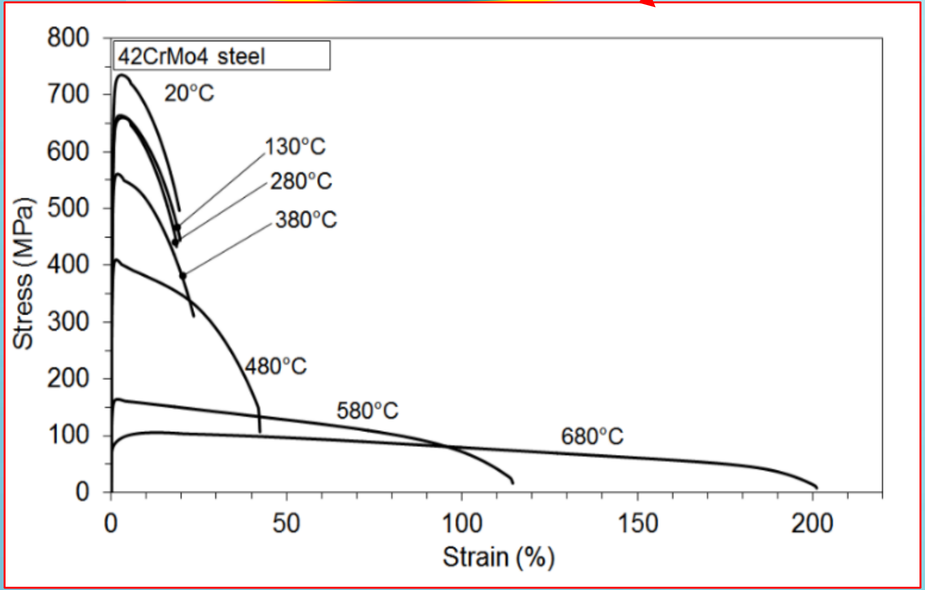
20MnCr5



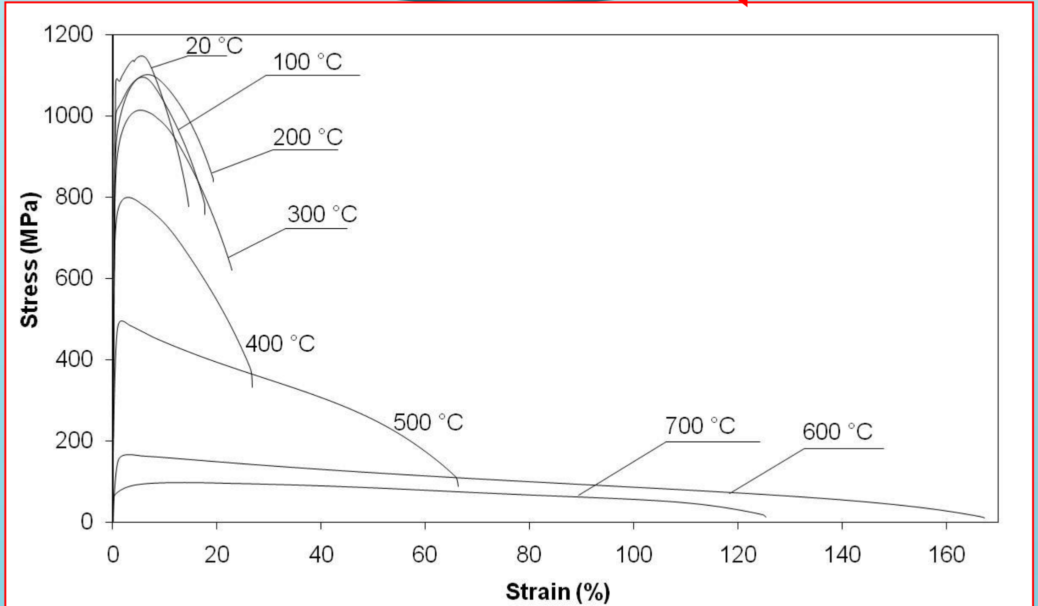
51CrV4



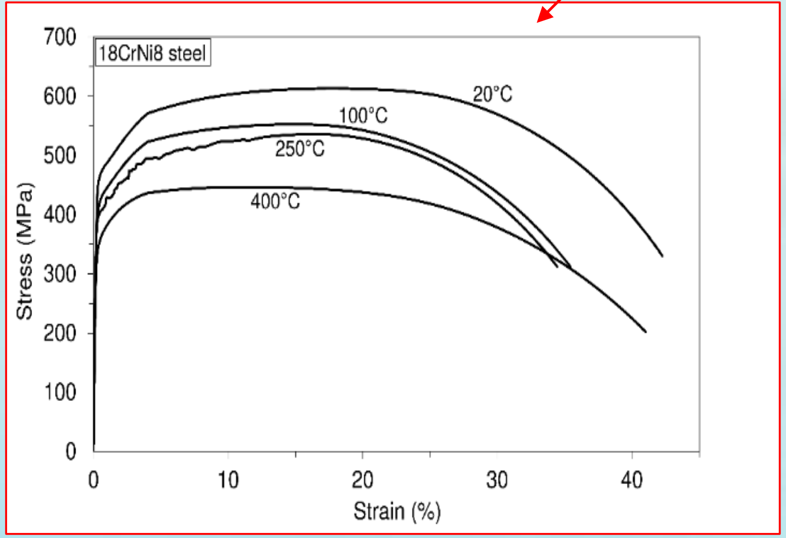
42CrMo4

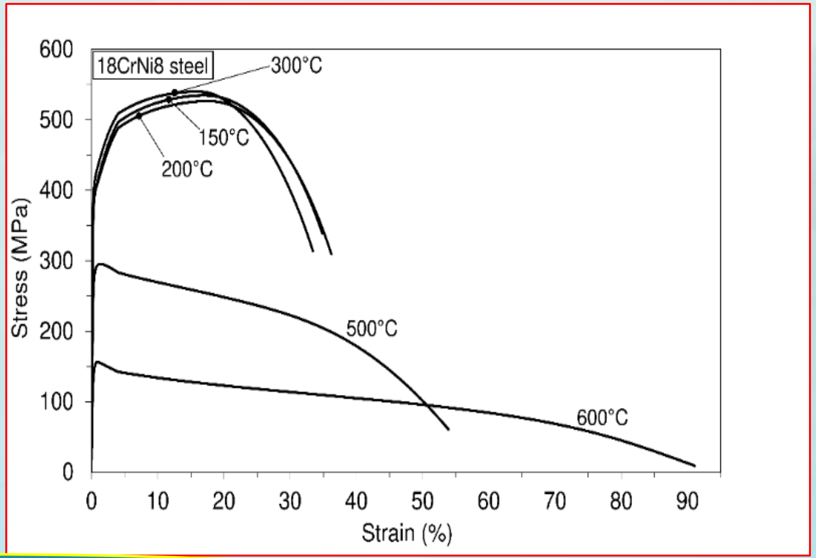


50CrMo4

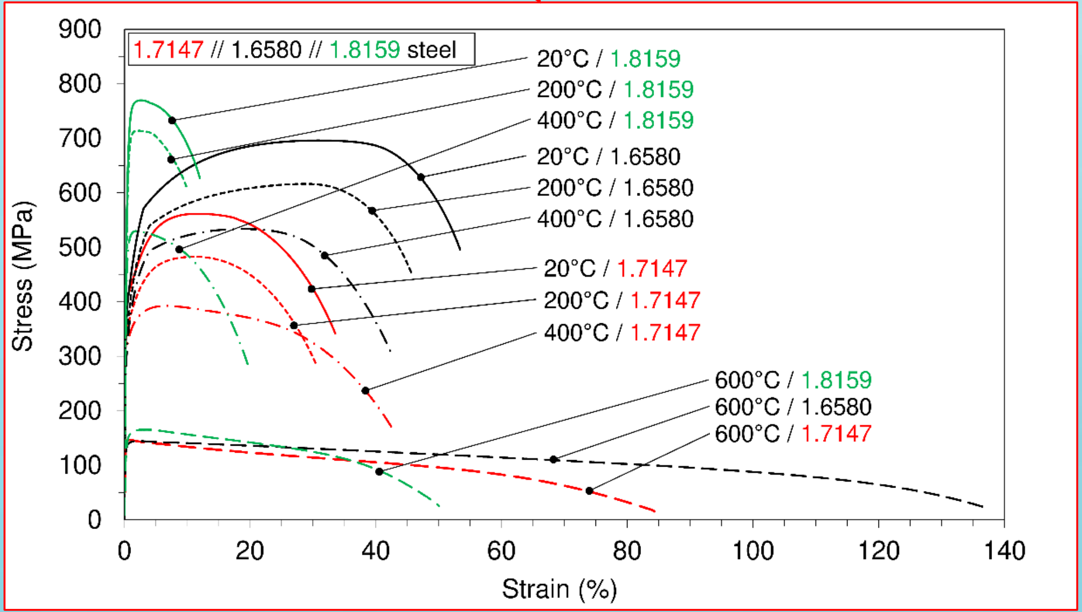


18CrNi8





Comparison of some materials

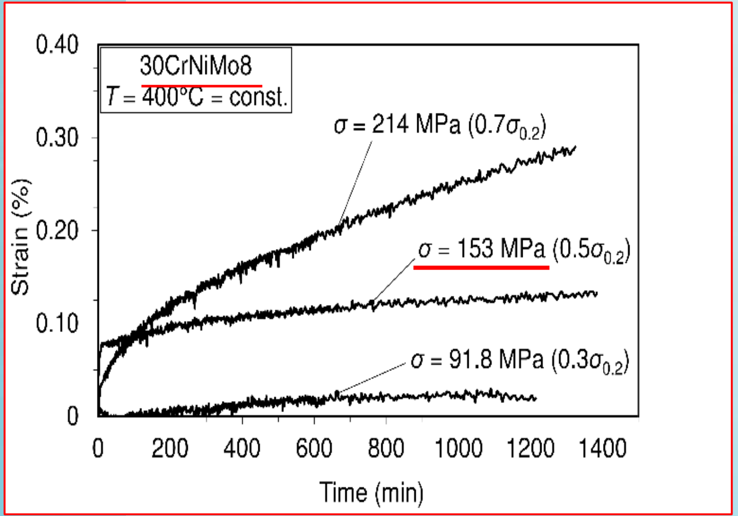


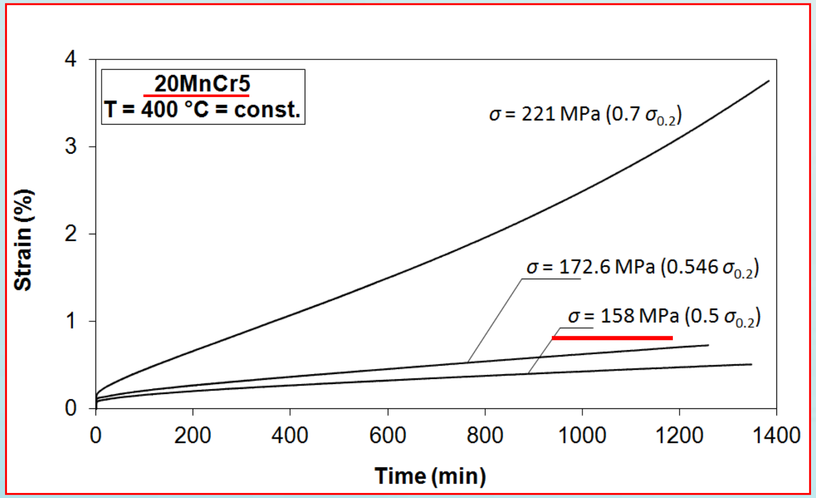
Temperature dependence of mechanical properties

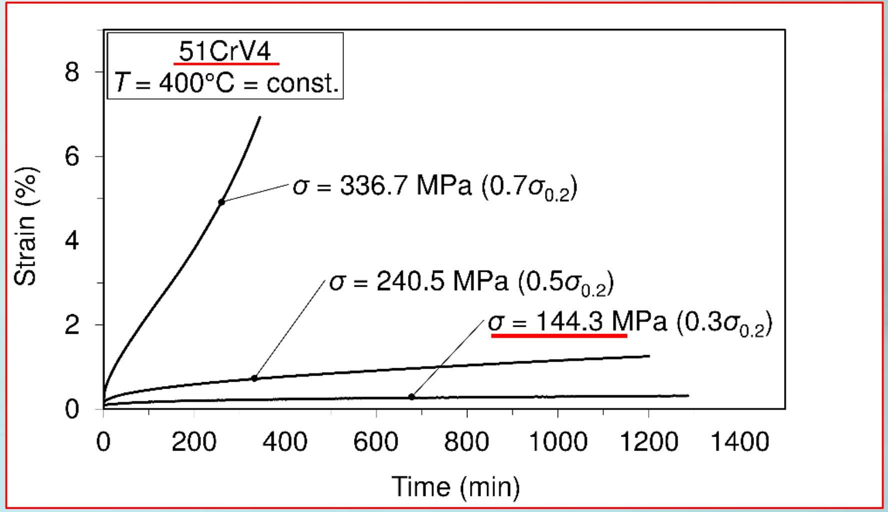
Mat	Temperature (°C)																				
	20			100			200			300			400			500			600		
	σ_m MPa	$\sigma_{0.2}$ MPa	E GPa	σ_m MPa	$\sigma_{0.2}$ MPa	E GPa	σ_m MPa	$\sigma_{0.2}$ MPa	E GPa	σ_m MPa	$\sigma_{0.2}$ MPa	E GPa	σ_m MPa	$\sigma_{0.2}$ MPa	E GPa	σ_m MPa	$\sigma_{0.2}$ MPa	E GPa	σ_m MPa	$\sigma_{0.2}$ MPa	E GPa
1.6580	696	383	217	634	355	199	616	350	190	702	365	184	534	307	160	303	228	147	145	130	115
1.7147	561	397	219	513	373	206	482	349	192	499	362	184	392	315	177	265	253	129	146	141	76
1.8159	770	642	198	730	592	192	714	608	182	727	613	172	530	481	165	334	291	139	165	141	63
1.7225	735	593	202	130/664	130/538	130/190	280/660	280/557	280/180	380/560	380/489	380/170	480/409	480/376	480/117	580/164	580/139	580/90	680/105	680/76	680/75
1.7228	1147	1090		1095	1005		1102	912	-	1014	850	-	799	694		495	437	-	165	114	-
1.5920	613	458	215	552	412	207	527	392	197	540	410	181	447	349	176	295	276	139	156	141	81

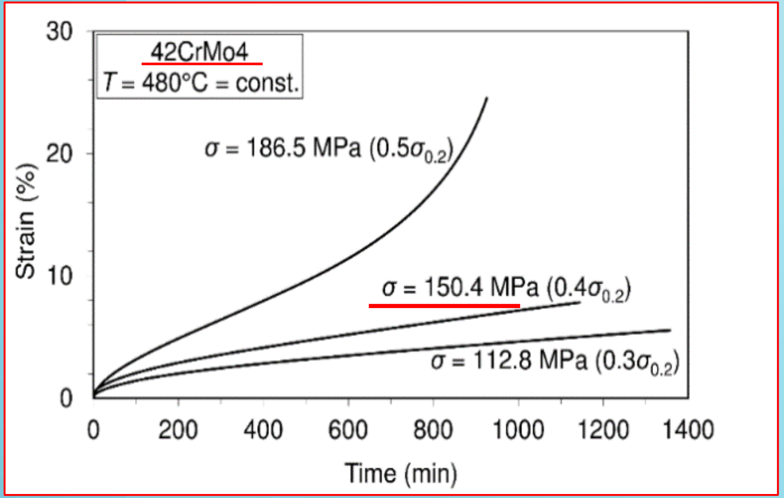
Creep behavior - comparison

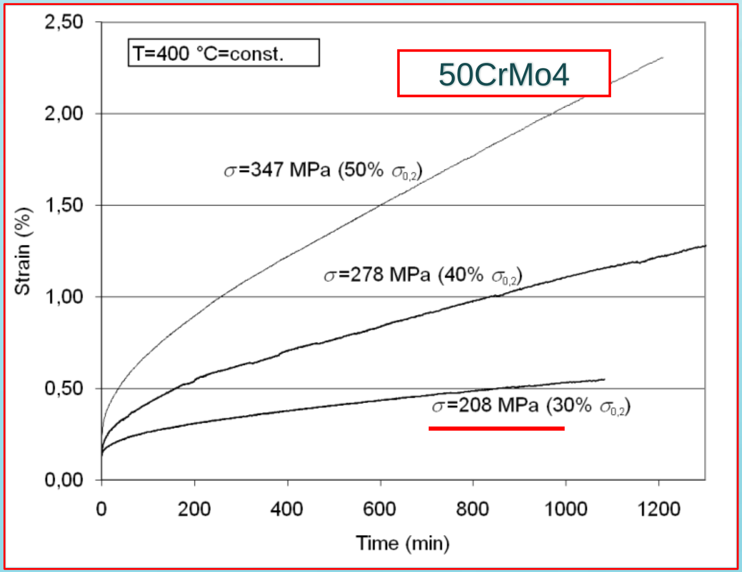
400°C

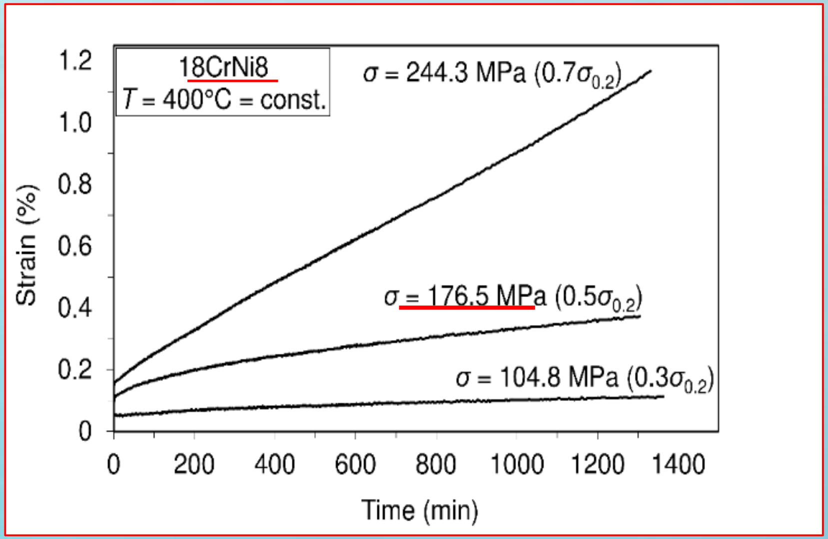




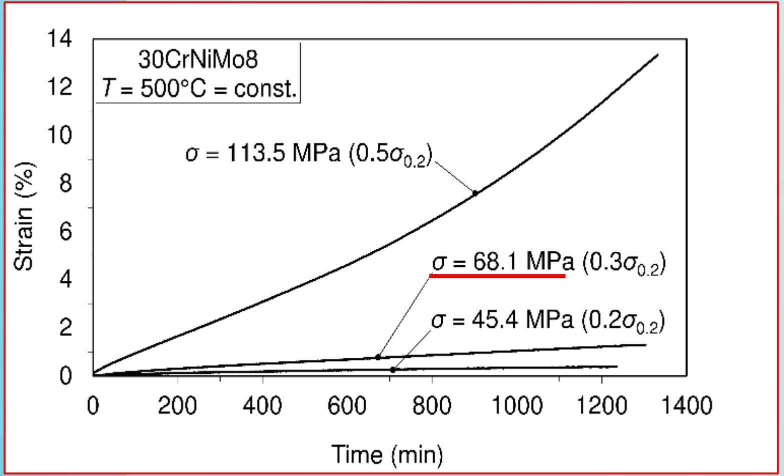


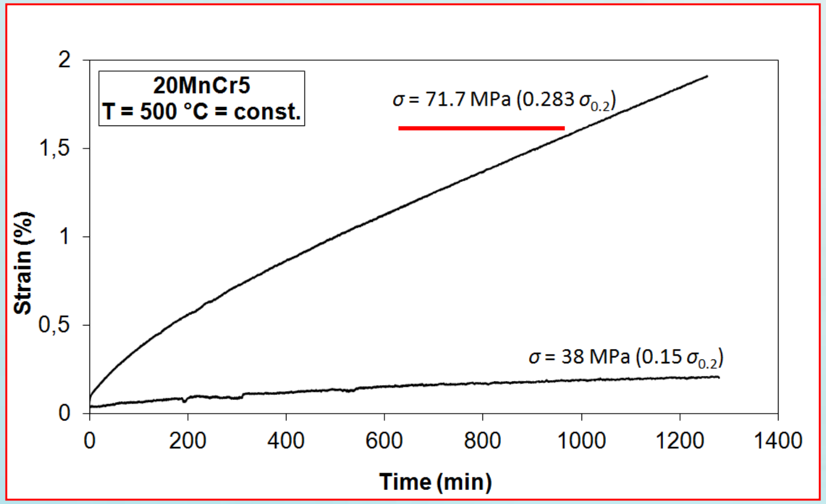


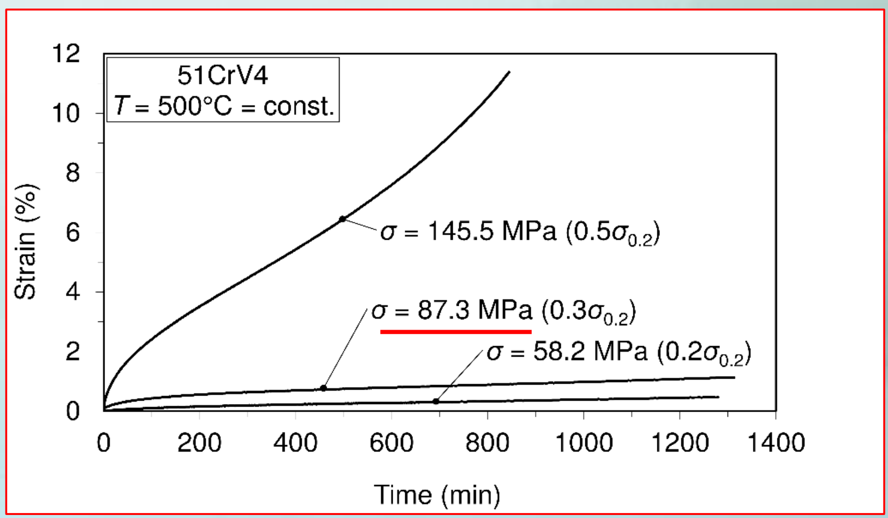


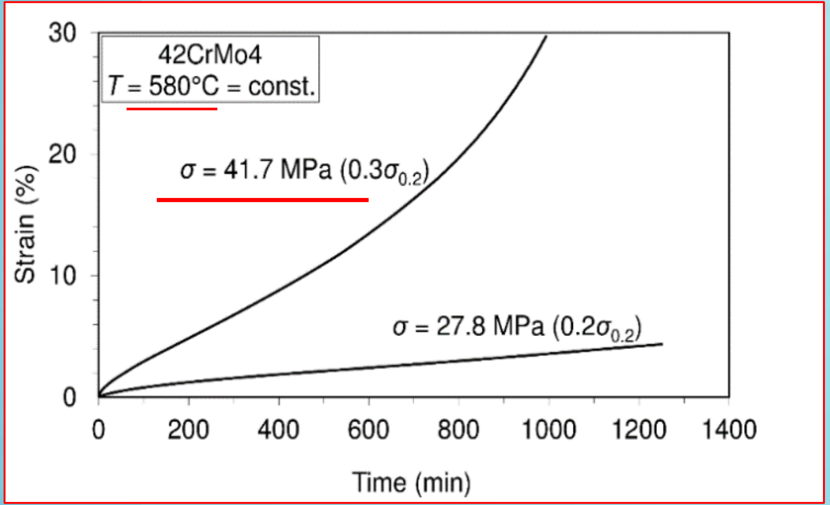


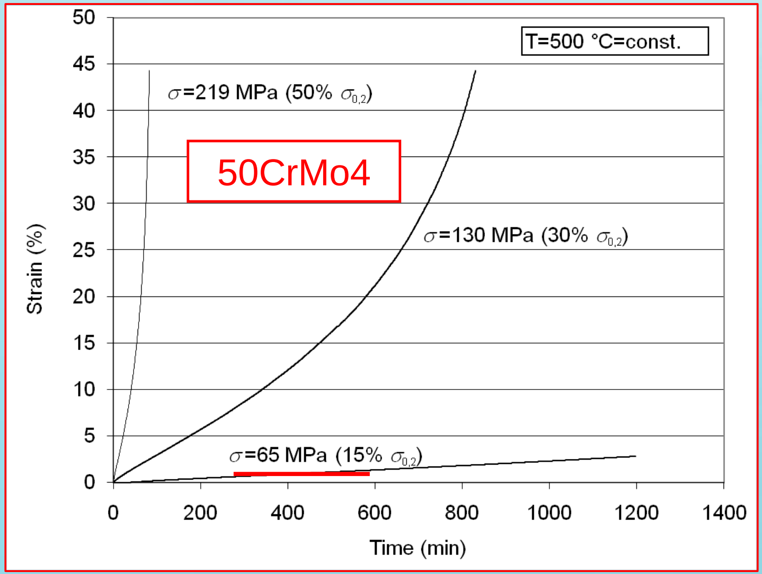
500°C

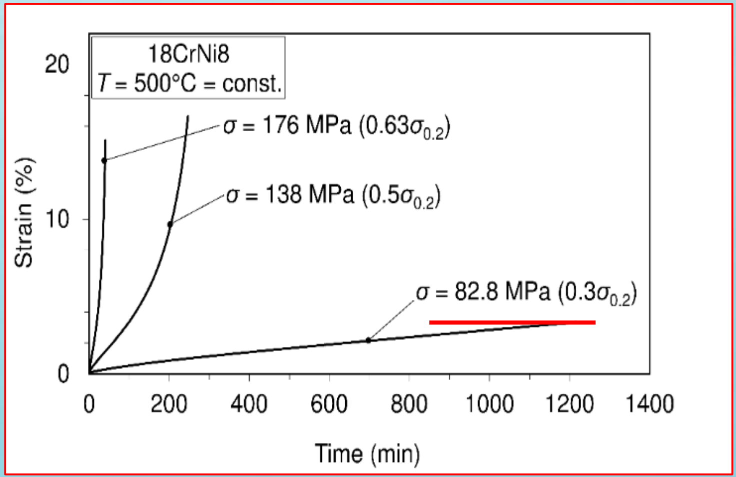

30CrNiMo8
T = 500°C = const.
σ = 113.5 MPa (0.5σ0.2)
σ = 68.1 MPa (0.3σ0.2)
σ = 45.4 MPa (0.2σ0.2)
Strain (%)
Time (min)


20MnCr5
T = 500 °C = const.
σ = 71.7 MPa (0.283 σ0.2)
σ = 38 MPa (0.15 σ0.2)
Strain (%)
Time (min)

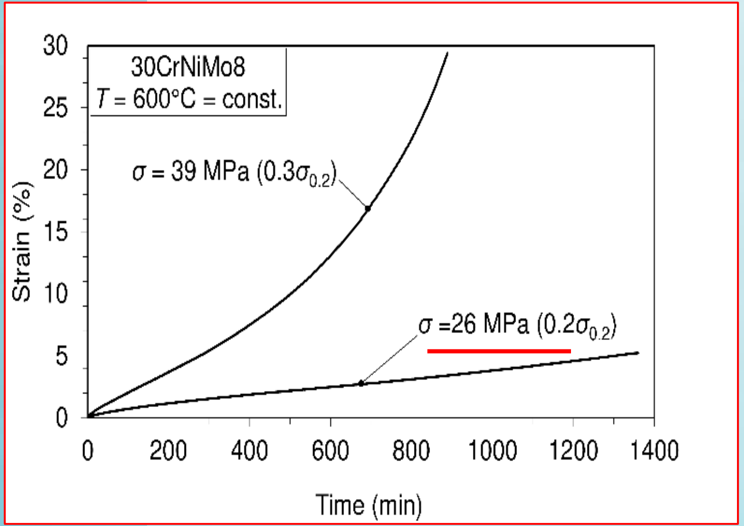

51CrV4
T = 500°C = const.
σ = 145.5 MPa (0.5σ0.2)
σ = 87.3 MPa (0.3σ0.2)
σ = 58.2 MPa (0.2σ0.2)
Strain (%)
Time (min)

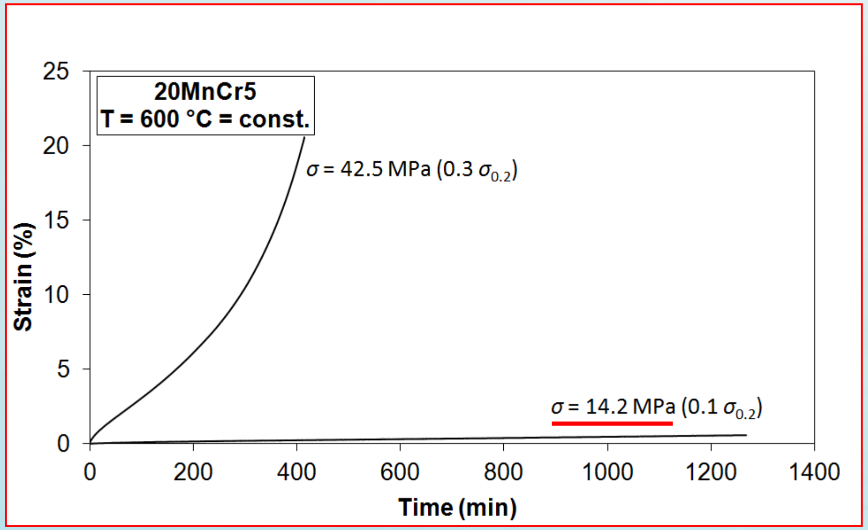

42CrMo4
T = 580°C = const.
σ = 41.7 MPa (0.3σ0.2)
σ = 27.8 MPa (0.2σ0.2)
Strain (%)
Time (min)

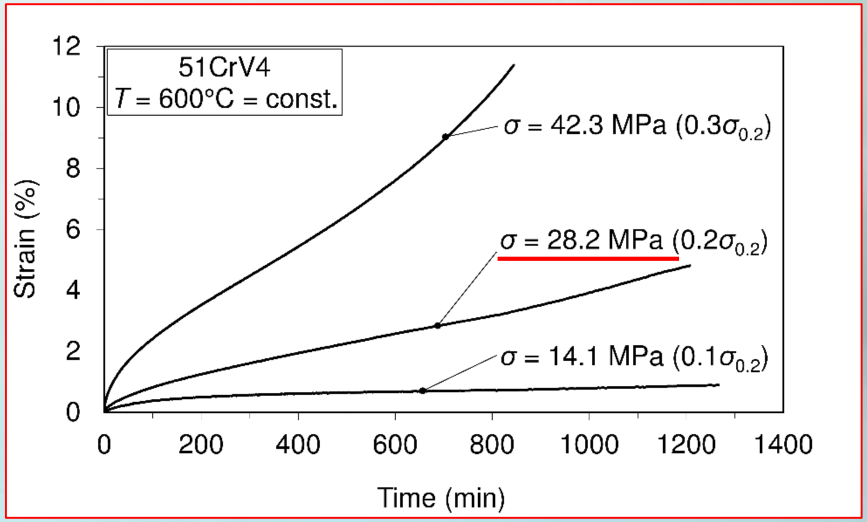

T=500 °C=const.
σ=219 MPa (50% σ0,2)
50CrMo4
σ=130 MPa (30% σ0,2)
σ=65 MPa (15% σ0,2)
Strain (%)
Time (min)

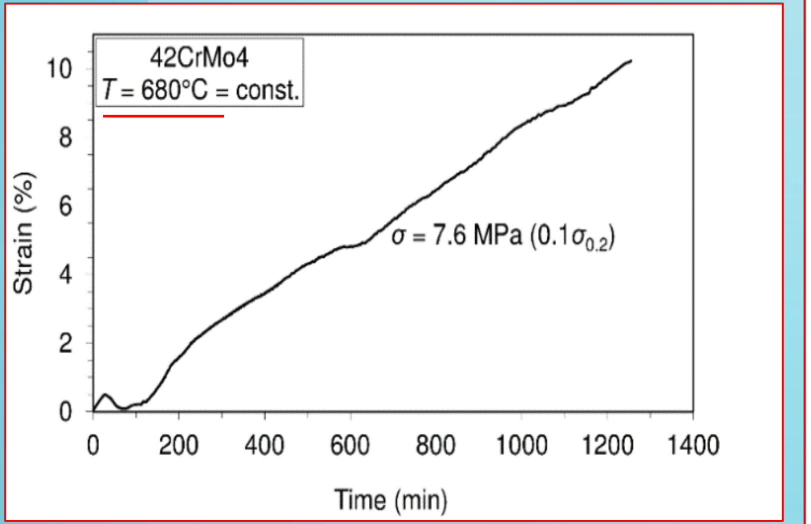

18CrNi8
T = 500°C = const.
σ = 176 MPa (0.63σ0.2)
σ = 138 MPa (0.5σ0.2)
σ = 82.8 MPa (0.3σ0.2)
Strain (%)
Time (min)

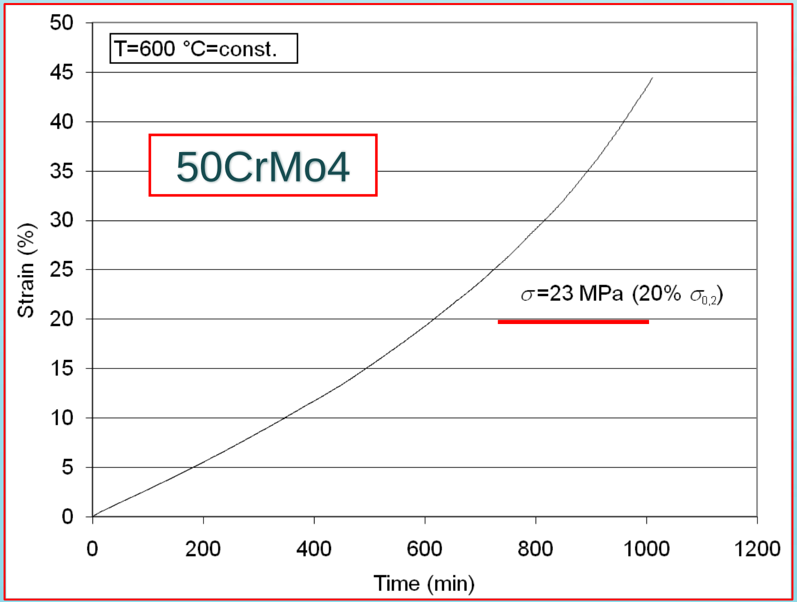
600°C

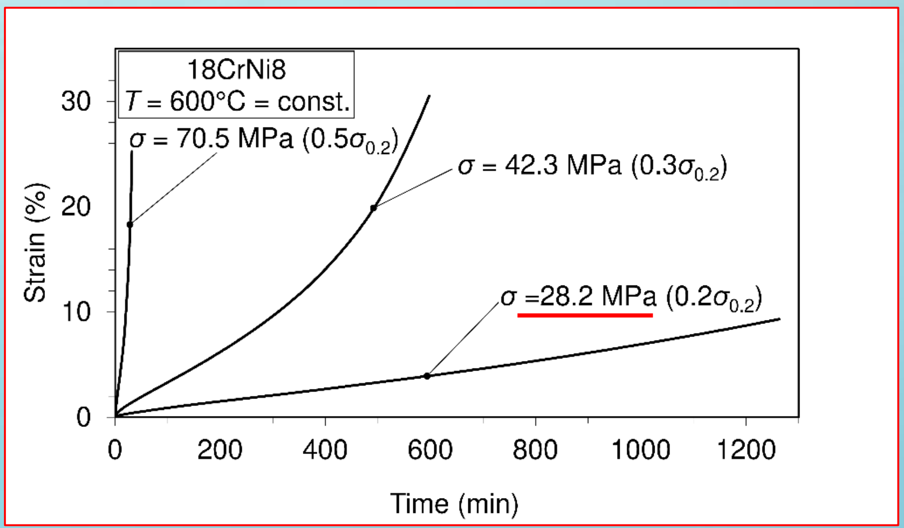

30CrNiMo8
T = 600°C = const.
σ = 39 MPa (0.3σ0.2)
σ =26 MPa (0.2σ0.2)
Strain (%)
Time (min)


20MnCr5
T = 600 °C = const.
σ = 42.5 MPa (0.3 σ0.2)
σ = 14.2 MPa (0.1 σ0.2)
Strain (%)
Time (min)


51CrV4
T = 600°C = const.
σ = 42.3 MPa (0.3σ0.2)
σ = 28.2 MPa (0.2σ0.2)
σ = 14.1 MPa (0.1σ0.2)
Strain (%)
Time (min)


42CrMo4
T = 680°C = const.
σ = 7.6 MPa (0.1σ0.2)
Strain (%)
Time (min)


T=600 °C=const.
50CrMo4
σ=23 MPa (20% σ0.2)
Strain (%)
Time (min)

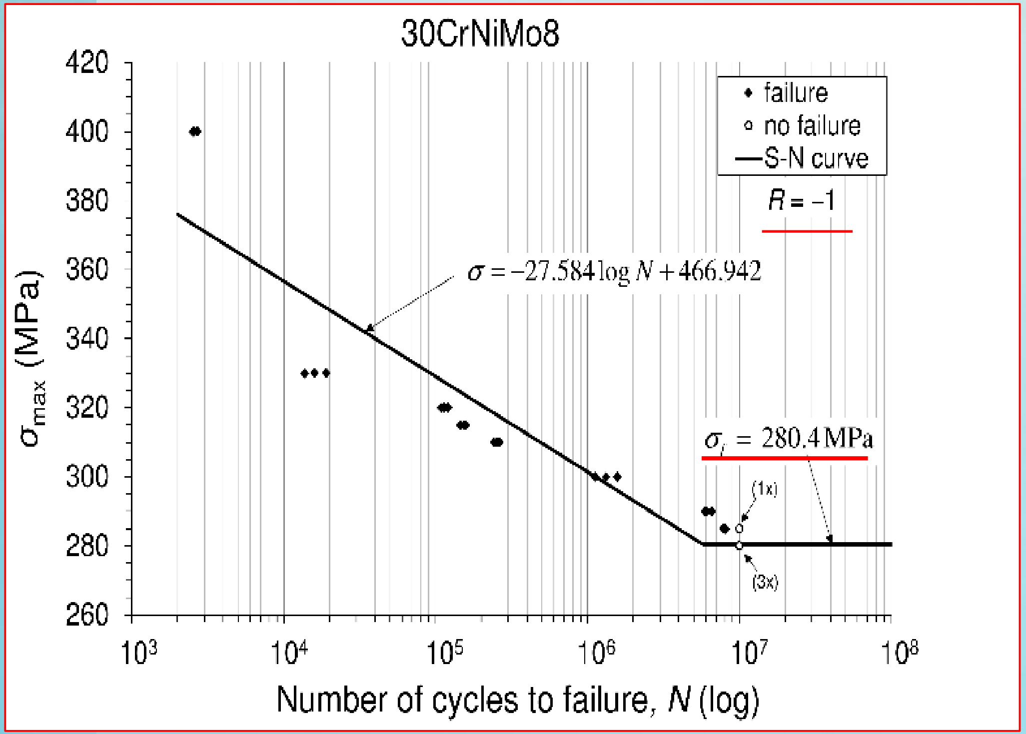

18CrNi8
T = 600°C = const.
σ = 70.5 MPa (0.5σ0.2)
σ = 42.3 MPa (0.3σ0.2)
σ =28.2 MPa (0.2σ0.2)
Strain (%)
Time (min)

Calculated fracture toughnes-based on tested impact energy (room temp)

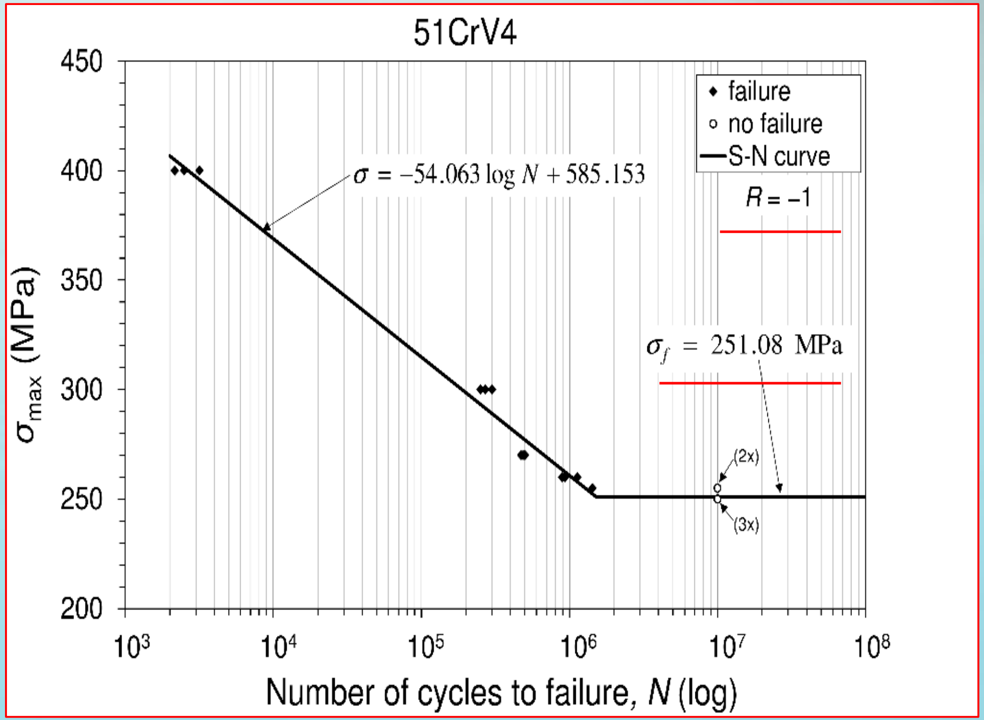
Material	**Charpy impact energy** $\boldsymbol{CVN\ (J)}$ $\boldsymbol{(V-notch), V=2mm}$	**Calculated farcture toughness** $K_{Ic}=8.47(CVN)^{0.63}$...(Roberts-Newton) $K_{Ic}\ (MPa\sqrt{m})$
30CrNiMo8	79	132.8
20MnCr5	178	221.6
51CrV4	24.5	63.5
42CrMo4 (but only soft annealed)	166	212
50CrMo4	69	122
18CrNi8	220	253

Fatigue testing, fatigue strength, fatigue limit

30CrNiMo8

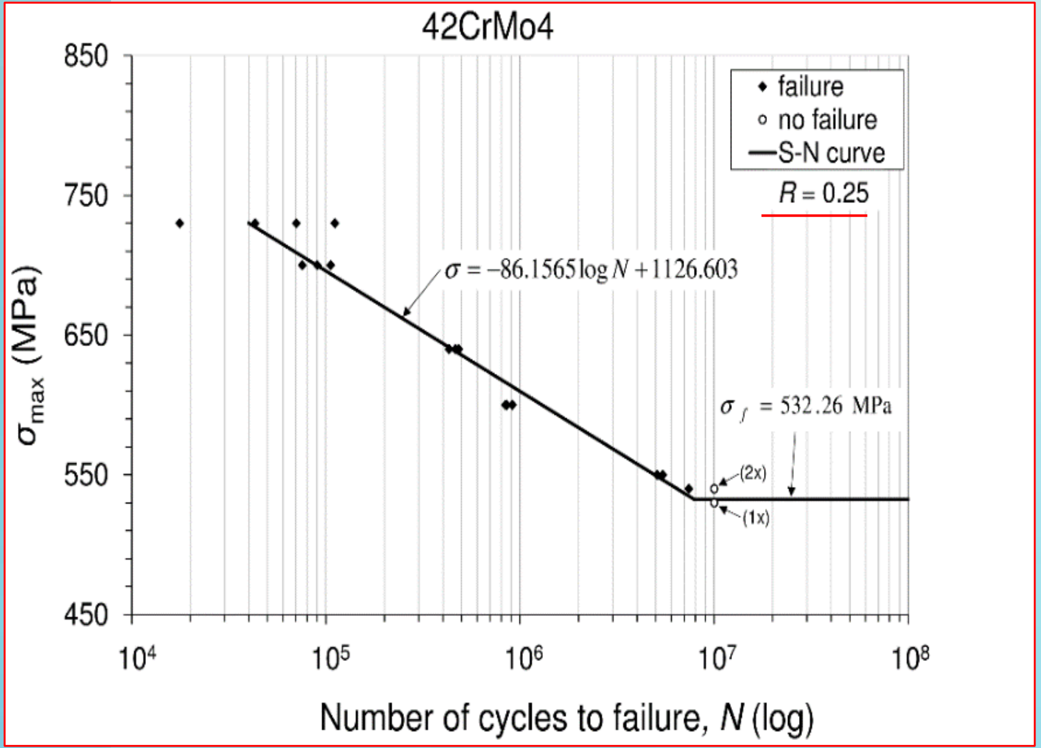


51CrV4

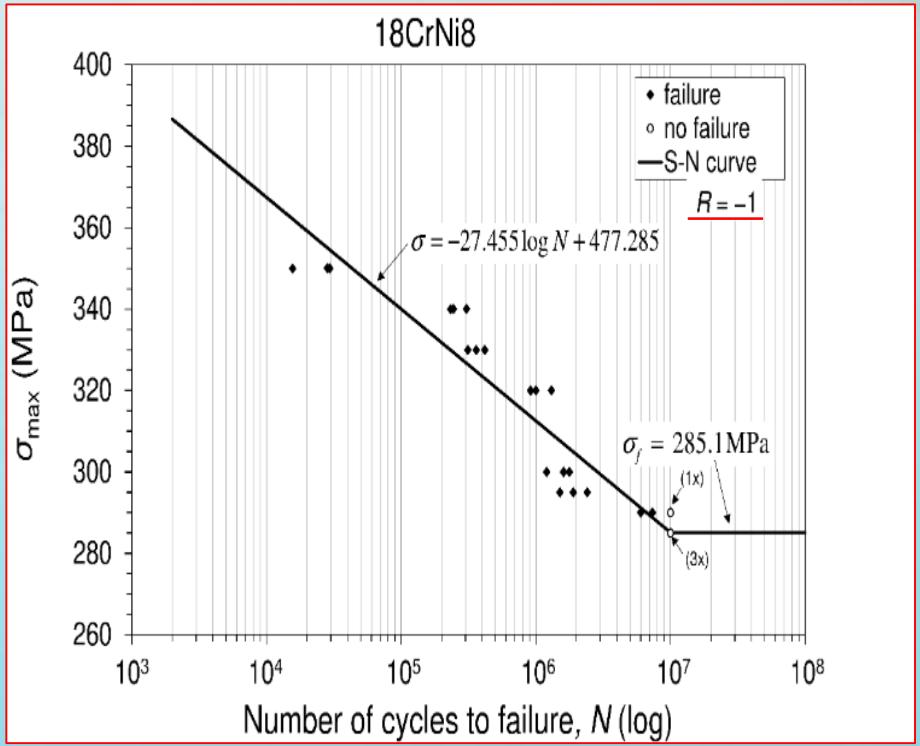


Fatigue testing, fatigue strength, fatigue limit

42CrMo4



18CrNi8



Fatigue limit calculation-modified staircase method

Case: 30CrNiMo8

Table: Data related to failed (♦) and non-failed (◦) specimens used in modified staircase method

Stress ratio $R=-1$, room temperature							
Stress σ_i/MPa	Specimen						
	1	2	3	4	5	6	7
290			♦		♦		♦
285		○		♦		♦	
280	○						

Table: Data analysis for modified staircase method (f $-$ $failed$)

Stress ratio $R=-1$, room temperature				
Stress σ_i/MPa	Stress level, i	f_i	if_i	i^2f_i
290	2	3	6	12
285	1	2	2	2
280	0	0	0	0
$\sum f_i, if_i, i^2f_i$		5	8	14

Table: Constants (*A*, *B*, *C* and *D*) according to ISO 12107

Stress ratio $R=-1$	
Formula	30CrNiMo8
$A=\sum i\cdot f_i$	8
$B=\sum i^2\cdot f_i$	14
$C=\sum f_i$	5
$D=\frac{B\cdot C-A^2}{C^2}$	0.24

$\sigma_{f(P,1-\alpha)}=\bar{\mu}_y-k_{(P,1-\alpha,)}\cdot\bar{\sigma}_y,$

$\bar{\mu}_y=\sigma_0+d\left(\frac{A}{C}-\frac{1}{2}\right)$...the mean fatigue strength

$\bar{\sigma}_y=1.62\cdot d(D+0.029)$...estimated stadard deviation of fatigue strength

$k_{(P,1-\alpha,\nu)}=k_{(0.1;0.9;6)}=2.333$

$\bar{\sigma}_y=1.62\cdot d(D+0.029)$

$R=-1\rightarrow\bar{\mu}_y=\sigma_0+d\left(\frac{A}{C}-\frac{1}{2}\right)$ = 280+5 (8/5 - 1/2) = 285.5 MPa

$R = -1 \rightarrow \bar{\sigma}_y = 1.62 \cdot d(D + 0.029)$ = 1.62· 5(0.24+0.029) = 2.179 MPa

Fatigue limit in accordance with eq. (3), is:

$R = -1 \rightarrow \sigma_{f(0.1;0.9;6)} = \bar{\mu}_y - k_{(P,1-\alpha,\nu)} \cdot \bar{\sigma}_y$ = 285.5 –2.333 · 2.
179 = 280.4 MPa.

Conclusions

Material	σ_m MPa		$\sigma_{0.2}$ MPa		Charpy energy & K_{Ic} CVN (J) /K_{Ic} $(MPa\sqrt{m})$	Creep resist. (at approx. $0.3\sigma_{0.2}$~70-80MPa)	Fatigue MPa
	T°C		T°C		T°C	T°C	T°C/$R=-1$
	20	500	20	500	20	500	20
30CrNiMo8	696	303	383	228	79/132.8	ok	280.4
20MnCr5	561	265	397	253	178/221.6	ok	-
51CrV4	770	334	642	291	24.5/63.5	ok	251
42CrMo4 (soft annealed)	735	580/164	593	580/139	166/212	not	532 ($R=0.25$): anneald and cold drawn)
50CrMo4	1147	495	1090	437	69/122	not	-
18CrNi8	613	295	458	276	220/253	ok	285

Acknowledgment

- This work has been financially supported by the University of Rijeka within the project: uniri-technic-18-42, “Investigation, analysis and modeling the behavior of structural elements stressed at room and high temperatures”

PLITVICE LAKES

DUBROVNIK

We are coming ftom Rijeka

THANK YOU FOR YOUR ATTENTION