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VERSION CREATED ON / VERSION / STATUS
10 May 2022 / 1.0 / Signed
EXTERNAL REFERENCE / VERSION

Guideline (not under Configuration Control)

Appendix_22 Guide to allowable strain in cryogenic piping and cryogen containing components

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Approval Process			
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Author	**Quinn E.**	**10 May 2022:signed**	**IO/DG/CP/PSP/VSP/VD**
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Information Protection Level: Non-Public - Unclassified RO: Croset Jean-Philippe			
Read Access	**GG: MAC Members and Experts, GG: STAC Members & Experts, AD: ITER, AD: External Collaborators, AD: IO_Director-General, AD: External Management Advisory Board, AD: EUROfusion-DEMO, AD: IDM_Controller, AD: members-DA, AD: Auditors, AD: ITER Management Assessor, project administrator, RO**		

#drn#

Change Log			
Appendix_22 Guide to allowable strain in cryogenic piping and cryogen containing components (7RAR3D)			
Version	***Latest Status***	***Issue Date***	***Description of Change***
v0.0	In Work	10 May 2022	
v1.0	Signed	10 May 2022	First version

ITER Vacuum Handbook
Appendix 22

Guide to allowable strain in cryogenic piping and cryogen containing components.

	Name	Affiliation
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1 Background

Helium leakage from cryogenic pipework within the ITER cryostat, cryo-pumps, cryo-lines, feeders or cold valve boxes could severely affect ITER's operational mission. Most critical is leakage within the ITER cryostat due to the complexity to both find and repair leaks. When austenitic stainless steel tube or pipes are cold worked then there are two changes which can occur which may lead to an increased risk of future leakage:-

1) The cold working can lead to a transition from austenitic to martensitic steel. This transition may only occur when the pipe is cooled to cryogenic temperatures. On cooling to cryogenic temperature the cold formed parts can have reduced ductility and are brittle. They may also then be effect by a magnetic environment.
2) The cold working can lead to intergranular corrosion with the precipitation of chromium. This is an issue if the cold worked areas are subsequently welded.

2 Requirement

Helium containing parts made from stainless steel 304L, 304LN,EN1.4306,EN1.4307, where the deformation from cold working is ≥ 12 % (100x tube OD/bend diameter) shall be solution annealed if it is to be used at cryogenic temperature.

Helium containing parts made from stainless steel 316L, 316LN,EN1.4404,EN1.4429,EN1.4435, where the deformation from cold working is ≥ 24 % (100x tube OD/bend diameter) shall be solution annealed if it is to be used at cryogenic temperature <70K.

Note:- in cold worked pipes where the above limits are exceeded, solution annealing can only be avoided if there is no welding in the strained areas and no operational flexing or stress on the pipe or that it can be proven that no significant austenitic to martensitic transformation has or will occur at the operating temperature.

3 Solution annealing

The annealing temperature shall be 1050°C ≤ T ≤1150 °C during a short heating time followed by a rapid cooling down to reach 500°C in 10 min maximum for 304/316L stainless steel. The annealing shall be performed in an inert atmosphere – argon or nitrogen can be used.

4 Basis of the requirements

It was advised by a leading engineer from one the largest cryogenic company that it was the practice to solution annealing components made from stainless steel where the cold work resulted in a strain greater than 12 % in any critical cryogenic application. The company data substantiating this is not openly available and hence it is investigated from other sources below.

4.1 Austenitic steels can be metastable and are susceptible to martensitic transformation by [6]:-

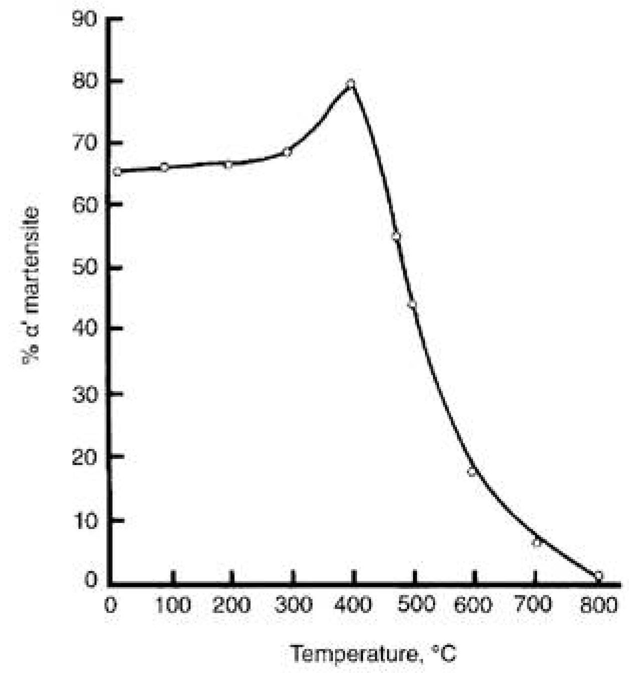
- Cooling below ambient
- Elastic stress
- Deformation
- Combination of the above

4.2 Higher alloying of the stainless steel prompts more stable austenite [6]:

- 304L (1.4306/1.4307) metastable
- 316L (1.4404/1.4429/1.4435) slightly metastable
- 310 stable

4.3 Cold work at room temperature enhances martensitic transformation (decreases austenite stability) at cryogenic temperature.

- For slightly metastable austenite testing at LN (77K) cannot be used for to indicate results and performance at lower temperature (e.g. 4K).
- Some material experts indicate a ratchet effect on repeated cooling.
- Once martensite has been formed reversion will not happen until above ~400°C (673K) [1]



- **Fig. 5** Reversion of martensite formed by cold work. Source: Ref 8

- **Figure 1 From [1]**

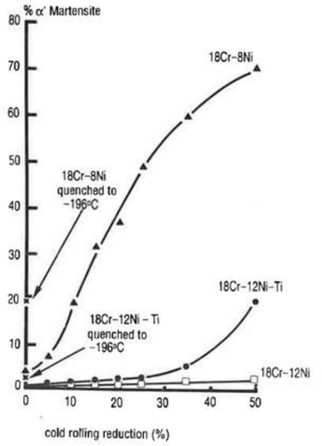


Fig. 14. — Effect of room temperature rolling reduction and cryogenic treatment at - 196 °C on the amount of α′ martensite in three austenitic stainless steels [2].

- **Figure 2 from [3]**

4.4 SS304L the Effect of Martensitic Transformation.

The martensitic transformation in 304L is well documented and several published results show a clear relationship between cold work and transformation temperature [1],[2],[3]. This can bee seen in the figure 2 above and figure 3 below.

12% cold work is hence a recommended maximum strain for operation at cryogenic temperature <80K.

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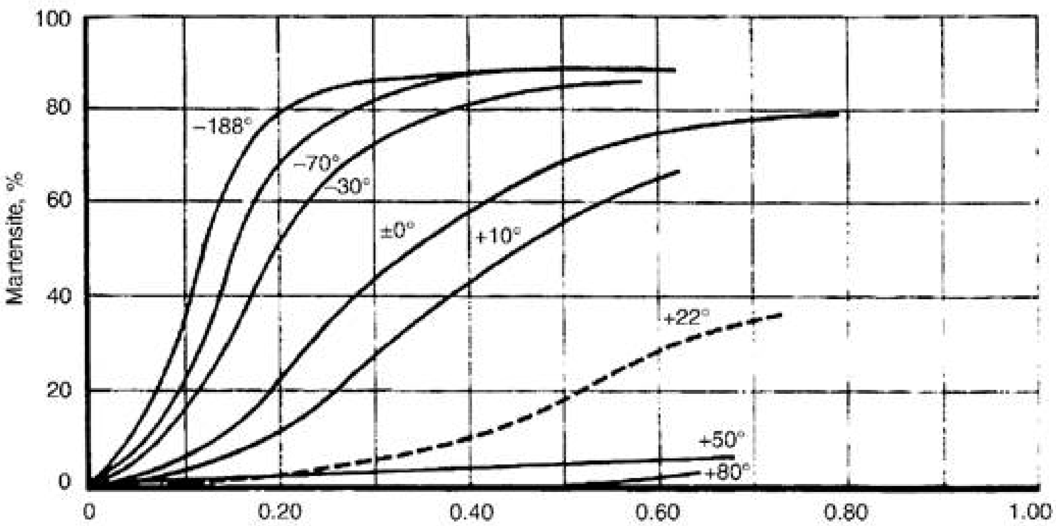
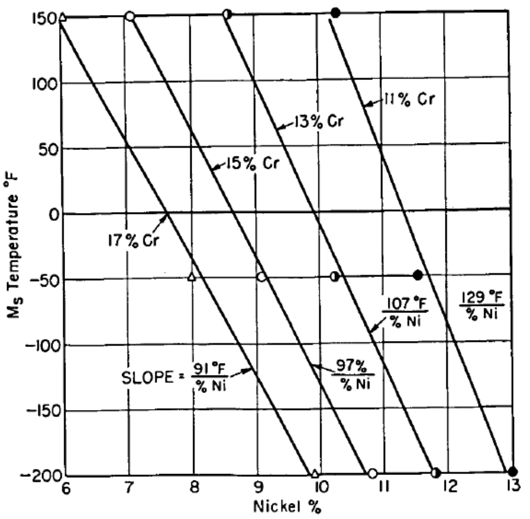


Fig. 4 Variation of martensite formation with temperature and true strain for 304. Source: Ref 7

- **Figure 3 from [1]**

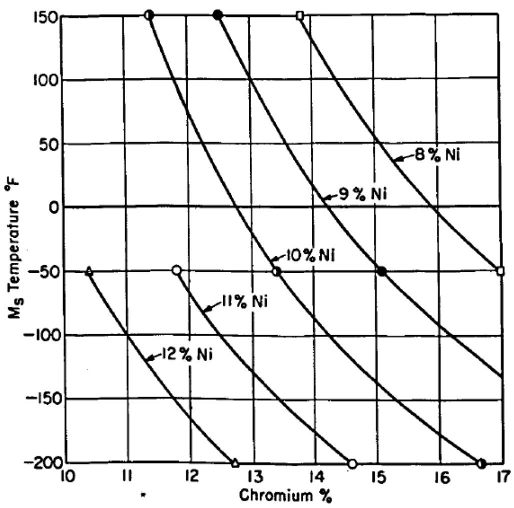
4.5 SS316L the Effect of martensitic transformation.

Figure 2 shows that with 12 % Ni the effect of martensitic transformation with strain at 80K is negligible but gives no information on cooling to lower temperatures. The effect of the alloy composition in stainless steels ranging between 11% and 18% Cr and between 8% and 12% Ni was investigated in [5]. The left diagram below depicts the reduction of the transition temperature M_s with increasing nickel content. The right diagram depicts the reduction of the transition temperature M_s with increasing chromium content. The formula for the transition temperature M_s presented in [5] gives for 316L (1.4404 or 1.4429 according to EN 10222-5) a transition temperature below 0K, hence no martensitic transformation occurs by cooling to the material, only with an additional elastic/plastic deformation will the martensitic transformation occur. However, there is no published test data that can be found which directly shows the 316 transformation temperature with cold work or the level of strain which is need to induce the transformation. This is likely due to the difficultly to perform such test at very low temperatures near 4K.



Corrected to a Nominal Composition of 1.33% Mn, 0.47% Si, 0.068% C+N, Balance Fe.

Fig. 10—Effect of Nickel on the M_s Temperature of Stainless Steel.



Corrected to a Nominal Composition of 1.33% Mn, 0.47% Si, 0.068%, Balance Fe.

Fig. 11—Effect of Chromium on the M_s Temperature of Stainless Steel.

In order to make a judgment of the level of acceptable strain a comparison between 304L and 316L can be made from data produced by a different test method from [4]. The two diagrams in Figure 4 below, show the austenite to martensitic transformation at different temperatures where the strain was induced at those temperatures. When the graphs are compared, the point where there is approximately 50% martensite phase in 304L coincides with the previously described 12% limit, and for 316L it can be seen that similarly the same point is at around 24% strain for 4 K. So it is reasonable to conclude that for 316L at 4K then solution annealing is required if the strain from cold work is above 24 %.

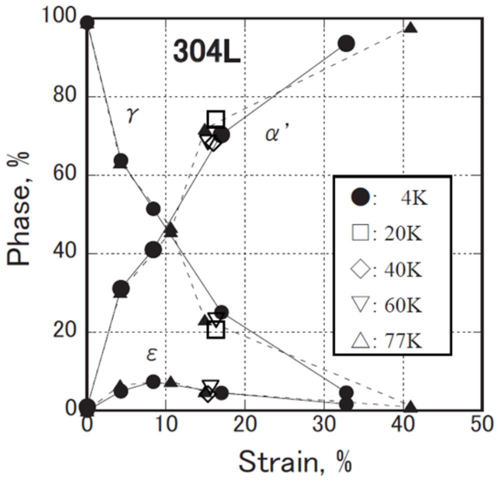


Fig. 12 Volume fractions of the ε- and α' -martensite for SUS 304L obtained by X-ray diffraction analysis of samples deformed at 4 K to 77 K.

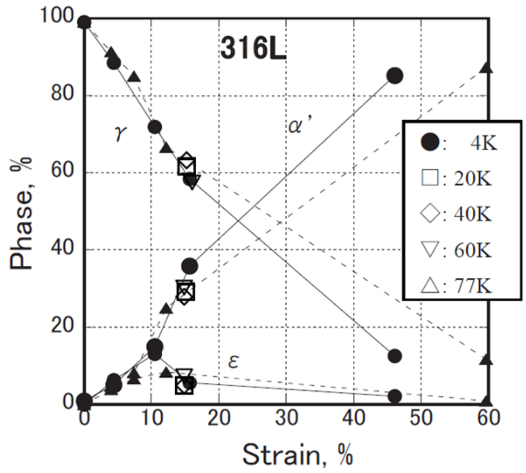


Fig. 13 Volume fractions of the ε- and α' -martensite for SUS 316L obtained by X-ray diffraction analysis of samples deformed at 4 K to 77 K.

- **Figure 4 from [4]**

References

[1] McGuire, MF., 2008,Stainless Steel for Design Engineers, ASM International, ch.6 Austenitic Stainless Steels.

[2] Lebedev, AA., Kosarchuk VV.,2000, Influence of phase transformations on the mechanical properties of austenitic stainless steels, International Journal of Plasticity,v16, p749-67

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[4] Ogata,T.,Yuri,T.,Ono,Y., 2007, Load-Displacement Curves, Specimen Heating and Strain induced Martensitic Transformations of Austenitic Stainless Steels at Cryogenic Temperatures.

[5] Eichelmann, Hull, 1952; The effect of composition on the temperature of spontaneous transformation of austenite to martensite in 18-8 type stainless steels

[6] Material Studies for magnetic fusion energy applications at low temperatures-VI, pages 11-39