Note on the sensitivity of stainless steels to strain rate

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There are only a few published results on the sensitivity of stainless steel to strain rate where the testing procedures are fully documented [2,3,6,7]. Other results are given in review documents [1,4,9] with limited information on testing conditions. Some reports [5,6,8] are internal ones with limited availability. More than half of the references are in Swedish, a language available only to the few.
Data reported for strains <0.2% and for strains > 10% have been omitted. The uncertainty in the data for small permanent deformation is likely too high and of doubtful value. Strains up to 10% have been shown to be relevant in crash situations and the focus of this study has thus been on strains between 0.2 and 10 %.
Data for strains at R_m have also been omitted since the strain value at R_m itself is strain dependant.

Austenitic grades; AISI 304 and 316 in annealed condition.

AvestaPolarit [1] has reported data for AISI 304 tested in tension at 0.2 and 2.0 % flow stress.

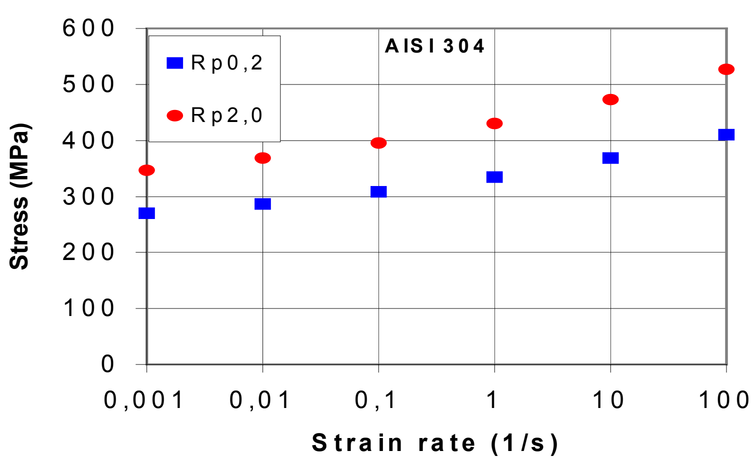

Figure 1. The flow stress at 0.2 and 2.0 % strain vs. strain rate for AISI 304.

The Cowper-Symonds model ,

$$\sigma = \sigma_0 \left[1 + \left(\frac{\dot{\varepsilon}}{D} \right)^{1/q} \right] \qquad \textbf{equ. (1)}$$

represent the data for the 304 material in Fig. 1 with D=100 , q=10 and σ_o= 205 and 264 for $\sigma_{p0.2}$ and $\sigma_{p2.0}$ respectively.

Using the representation

$$\sigma = \sigma_0 + k * \log \dot{\varepsilon}_p \qquad \textbf{equ. (2)}$$

the strain rate coefficient (k) is 32 and 41 MPa for 0.2 and 2.0 % strain respectively.

Ishikawa, Tanimura and Fukunaga [2] have reported tests on thin walled tubular specimen of SUS 304N. Tests were done in torsion in the strain rate range of 10^{-3} to 10^{3} s^{-1}. Some of the results are shown in a revised form in Fig. 2. The strain rate coefficient (k) is calculated to be 22 MPa at $2\gamma^p = 2\%$ strain.

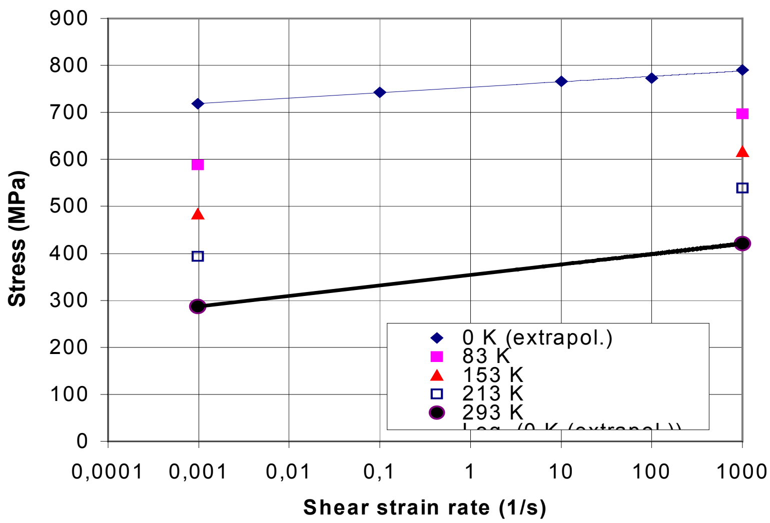

Figure 2. The flow stress at $2\gamma^p = 2\%$ strain vs. strain rate for SUS 304N.The graph is a combination of Fig. 5 and 6 of Ref.(2)

Data for AISI 316L ($R_{p0.2}$ = 259 MPa) tested in compression at 193, 243 and 293 °K are given by Hagström and Lindh-Ulmgren [3]. The RT-data (293 °K) are shown in Fig. 3.

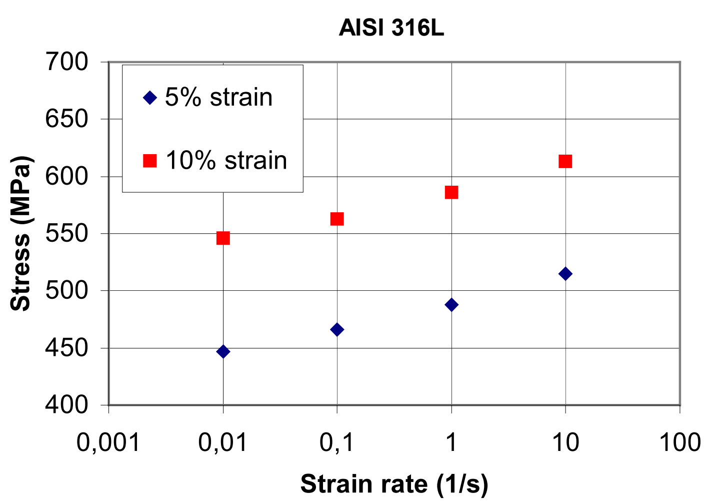

Figure 3. The flow stress at 5 and 10 % strain vs. strain rate for AISI 316L.

The slopes in this logarithmic representation (k-value in equ. 2) are 23 MPa for both strain levels.

SCI [4] has summarised the results of a programme of high strain rate tensile tests on AISI 316L. These results are given in graphic form in Fig. 4. The strain rate coefficient (k) is calculated to be 23 and 19 MPa for 0.2 and 1.0 % strain respectively.

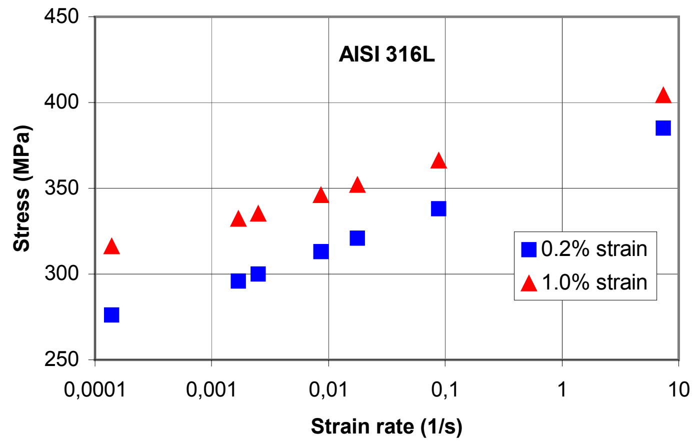

Figure 4. The flow stress at 0.2 and 1.0 % strain vs. strain rate for AISI 316L.

Austenitic grade AISI 301 in annealed and temper rolled conditions.

fka [5], Aachen has tested AISI 301LN in annealed condition ($R_{p0.2}$ = 400 MPa at 5 10^{-3} /s) within a EuroInox Automotive project. The tests were performed in tension at RT on 0.7 to 2.25 mm thick sheet. They have been evaluated for 2, 5 and 10% true strain and the results are shown in Fig. 5.

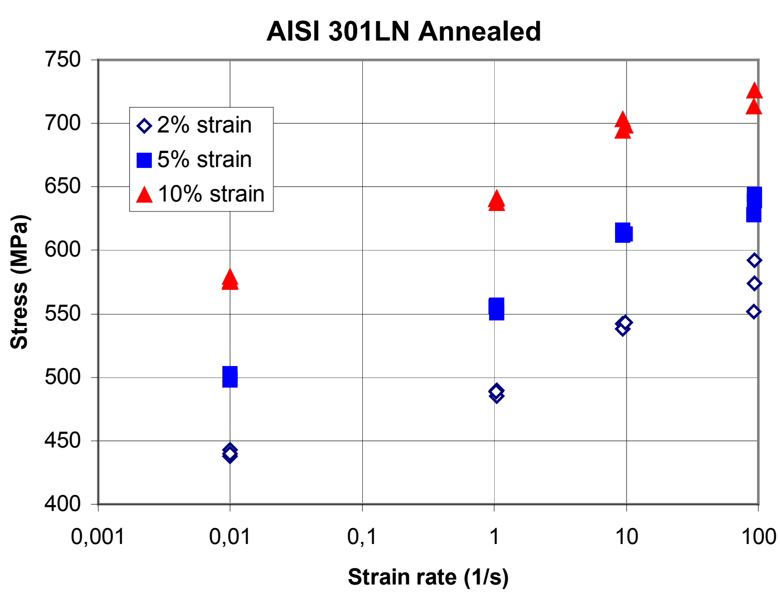

Figure 5. The flow stress at 2, 5 and 10 % strain vs. strain rate for AISI 301LN.

fka[5] has also tested temper rolled AISI 301LN C850 and C1000 in the same way as above. Results are given in Fig. 6 and 7.

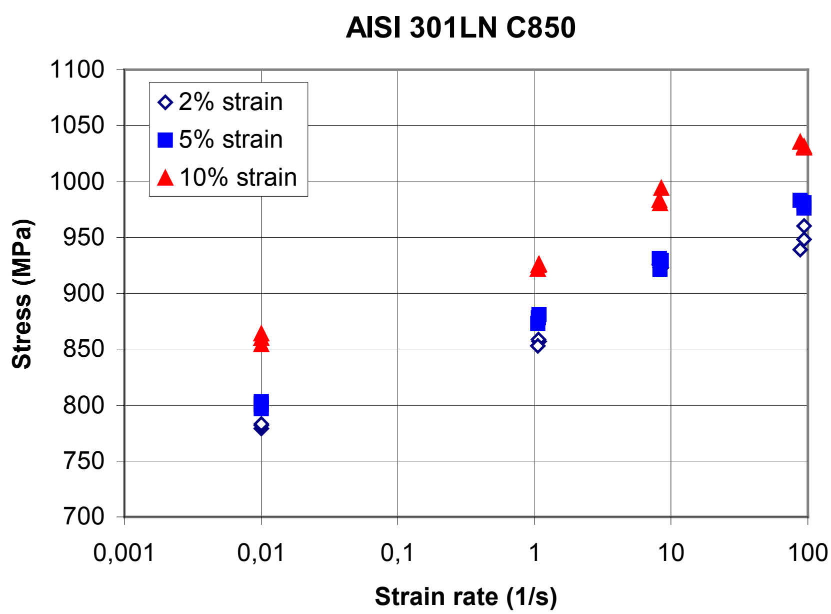

Figure 6. The flow stress at 2, 5 and 10 % strain vs. strain rate for AISI 301LN C850.

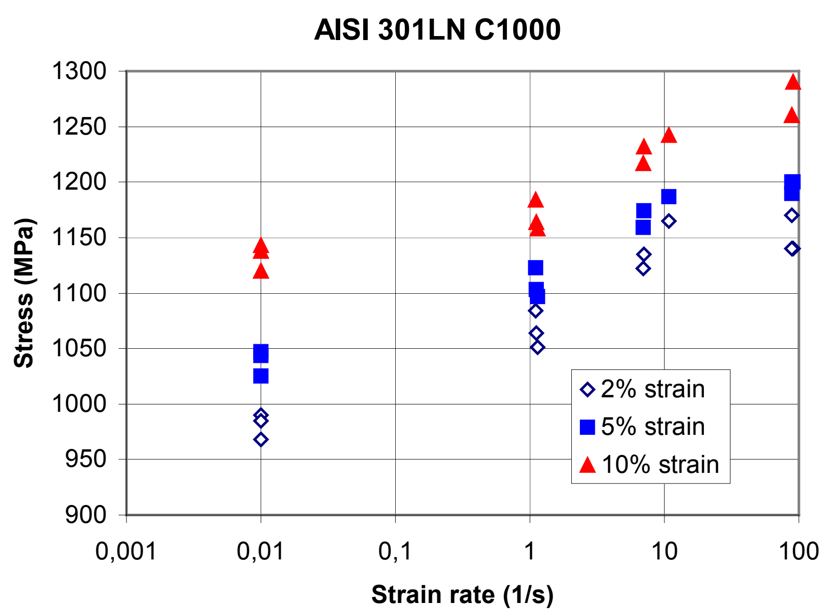

Figure 7. The flow stress at 2, 5 and 10 % strain vs. strain rate for AISI 301LN C1000.

k-values for the fka-results are given in Table I.

Table I Strain rate coefficient "k" for AISI 301LN (MPa).

	2 % strain	5 % strain	10 % strain
Annealed	34	36	38
C850	44	45	44
C1000	46	42	35

Schedin[6] has supplied data for the Outokumpu Stainless grade HyTens 1000 (AISI 301 C1000) in 1.6 mm thickness. Tests were done in the stain rate range of 0.01 to 300 s^{-1} using two specimens at each strain rate. In Fig. 8 typical stress-strain diagrams are shown.

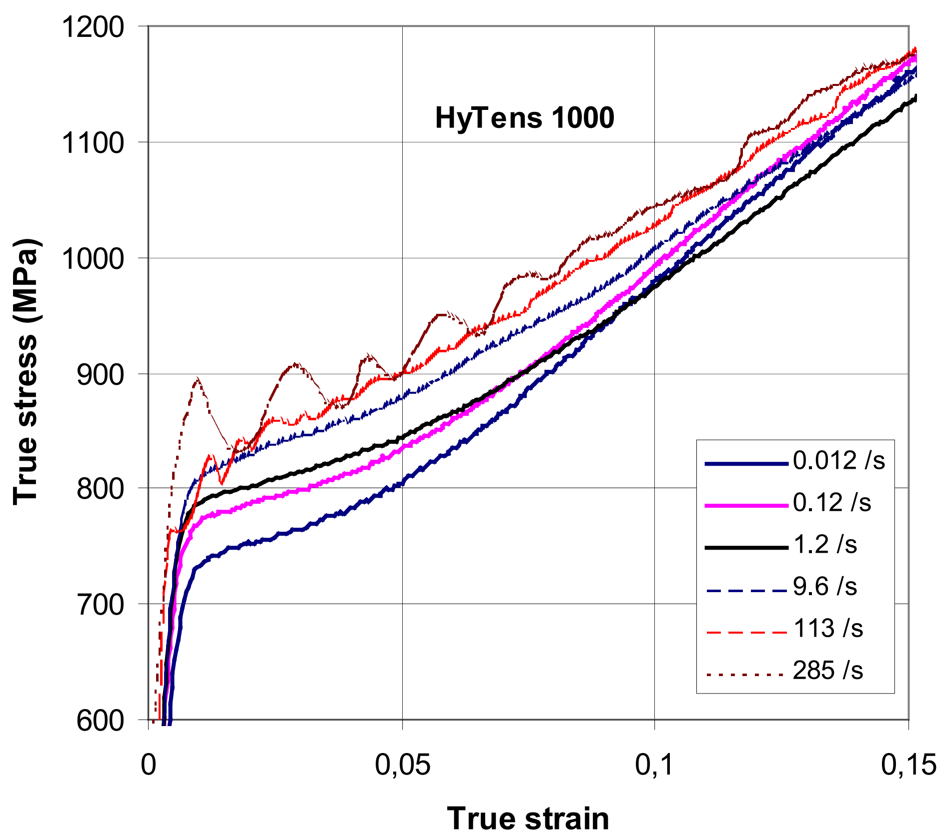

Figure 8. Stress-strain curves for HyTens 1000.

The curves are focused on the strain interval that are of interest for automotive impact calculations, e.g. strains up to about 10%. Note the resonance behavior at 113 and 285 s^{-1}. Similar behavior is observed in the fka[5]-results for AISI 301LN described earlier. The effect is due to an impact stress wave travelling through the specimen and, due to damping over the test duration, most pronounced at low strains. This could most probably be filtered out in the analysis but it is beyond the scope of this article and the ability of the author to do so. This effect does increase the uncertainty in the results for high strain rates. A least square fit procedure has been applied by the author to evaluate the curves for the two highest strain rates.

Fig. 8 demonstrates that the flow stress increases with increasing strain rate up to at least 10% true strain.
As shown in Fig. 9 the strain rate effect is less pronounced than in the fka[5] –results with strain rate coefficients of 21 and 25 MPa for 2 and 5% true strain. For 10% true strain the data cannot be represented by a single coefficient. Up to about a strain rate of 1 s^{-1} the flow stress is constant and for higher strain rates the coefficient is evaluated as 28 MPa.

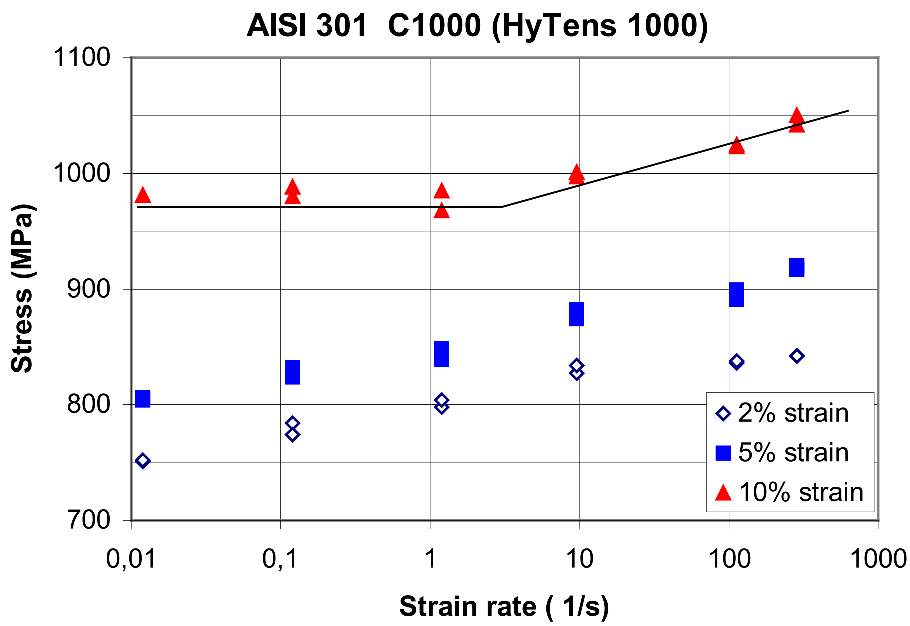

Figure 9. . The flow stress at 2, 5 and 10 % strain vs. strain rate for HyTens 1000 (AISI 301 C1000) *From Schedin*[6]**.**

Duplex grades; 2304 and 2205.

Gustafsson and Groth [8] have tested the two duplex grades 2304 and 2205 in the strain rate range 10^{-3} - 1 s^{-1} and evaluated results for 0.2 and 1.0 % strain. Tests were done in both the longitudinal (L) and transverse (T) directions from 4 mm thick sheets. Results are shown in Fig. 10 and 11.

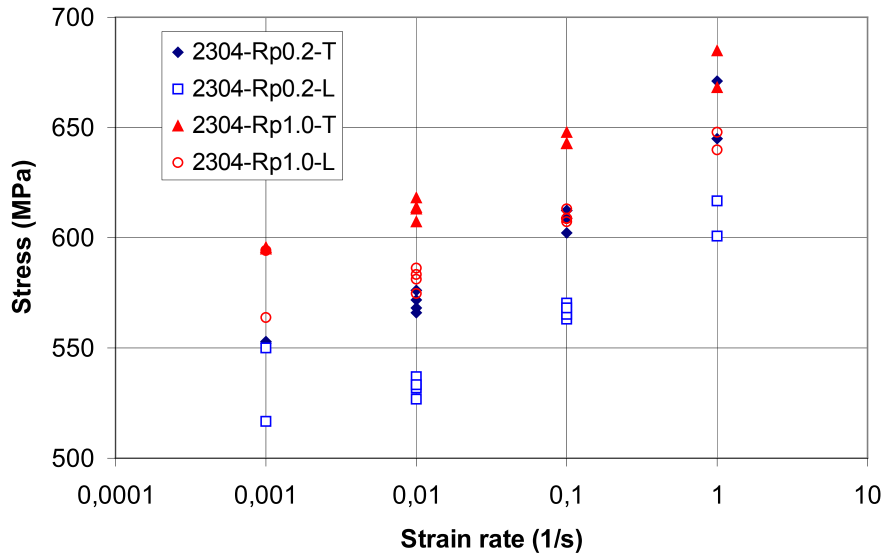

Figure 10. The flow stress at 0.2 and 1.0 strain for Duplex grade 2304.

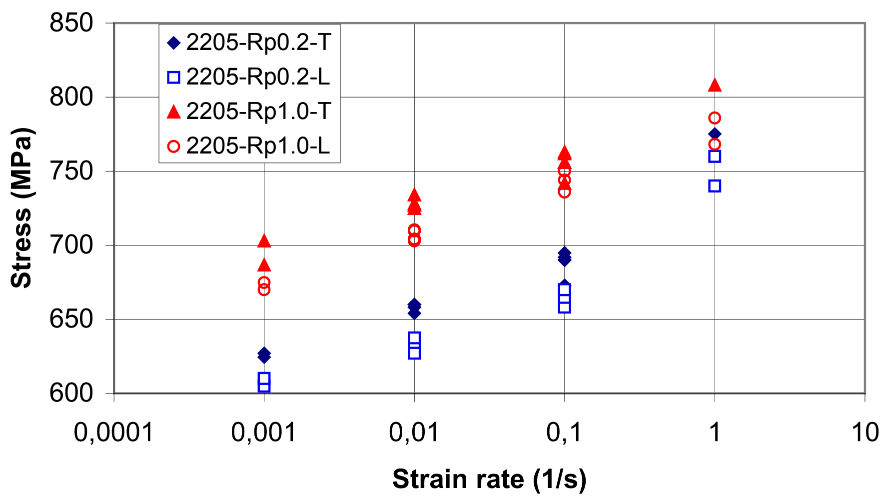

Figure 11. The flow stress at 0.2 and 1.0% true strain for Duplex grade 2205.

The strain rate coefficients for the different strains vary considerably with a mean value of about 30 MPa for both steel grades.
These results are also reported in Ref.(9) and evaluated according to the Cowper and Symonds representation with the results as in Table II.

Table II Cowper and Symonds constants for Duplex 2304 and 2205.

		2304L	2304T	2205L	2205T
$R_{p0.2}$	σ_0	$0.95 * R_{p0.2}$			
	D	400	300	100	100
	q	4	4	4	4
$R_{p1.0}$	σ_0	$0.97 * R_{p1.0}$			
	D	900	400	501	500
	q	4	3.6	3.61	3.6

Schedin[6] has also reported test results for the Duplex grade 2304. These have been evaluated at 2, 5 and 10% true strain with the results given in Fig. 12.
The strain rate coefficients are evaluated to be 38, 40 and 42 for 2, 5 and 10% true strain respectively.

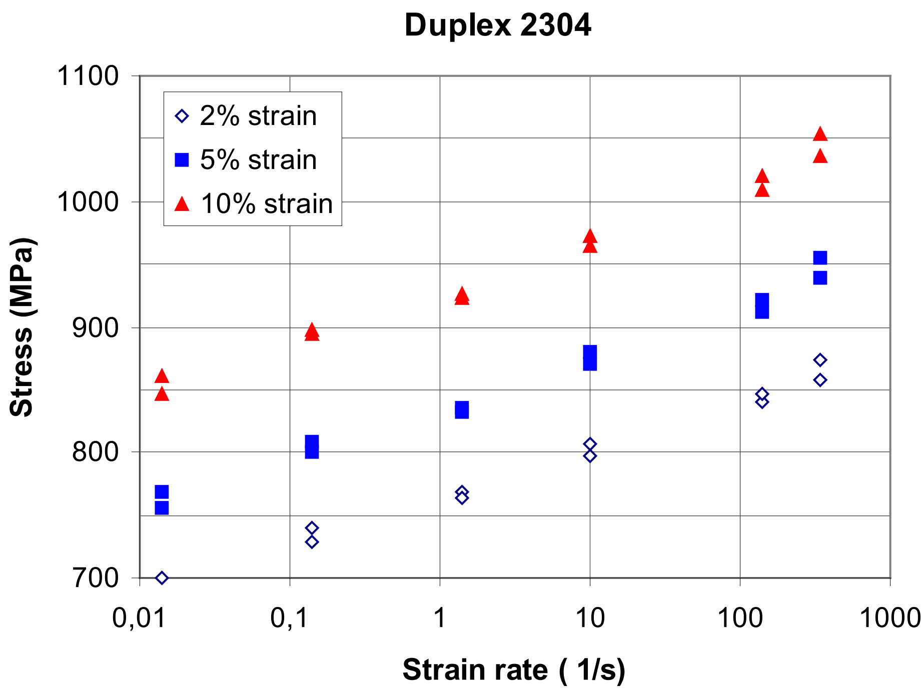

Figure 12. The flow stress at 2, 5 and 10% true strain for Duplex grade 2304.

Discussion

The reported data varies considerably. However, it has to be remembered that normal static strength variations within a plate are round 10 MPa and within a grade from one producer 20 – 30 MPa. Systematic errors between laboratories have also to be considered. These can easily reach 6-8 %. All these sources of error mean that the reproducibility of the stresses at high strain rates within a grade is limited. Even the stress increase due to a strain increase with specimens from a given sheet is expected to vary substantially. The k-value defined above is the measured mean increase of the flow stress due to a strain rate increase by a factor of 10 at a given strain. As seen above, these k-values vary, with a few exceptions, between 20 and 40 MPa.

In the author's opinion a good approximation of the flow stress (σ_p) at the strain ε_p and the strain rate $\dot{\varepsilon}_p$ is given for annealed austenitic and duplex stainless steels by:

$$\sigma_p = \sigma_{0p} + 30 * \log\left[\dot{\varepsilon}_p / 0.001\right] \quad \text{(MPa)} \qquad \text{equ. (3)}$$

or the equivalent expression

$$\sigma_p = \sigma_{0p} + 90 + 30 * \log \dot{\varepsilon}_p \quad \text{(MPa)} \qquad \text{equ. (3b)}$$

where σ_{0p} = static flow stress at the strain ε_p . Strain rate = 10^{-3} s^{-1}.

Equation (3) has an estimated uncertainty of $\pm 10 * \log \frac{\dot{\varepsilon}}{0.001}$ MPa.
This estimate together with its related uncertainty is shown in Fig.13 together with measured values from all studies above where sufficient testing and material information are known (Ref. 3,5,6 and 8). The 10% strain values for temper rolled AISI 301 and 301LN have been excluded.

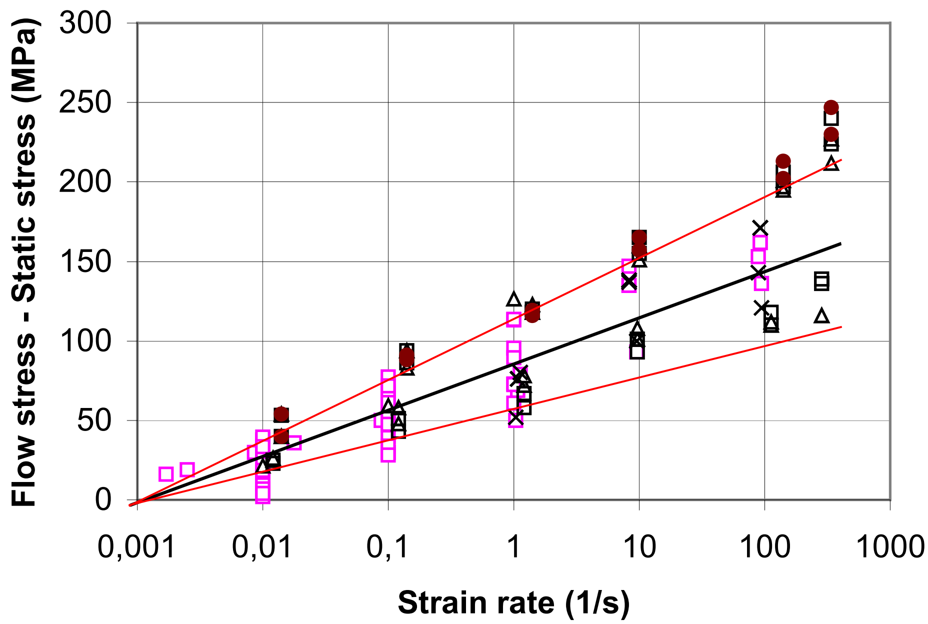

Figure 13. Increase in dynamic flow stress from the static flow stress for different strain rates.

For most stainless steels a conservative estimate (lower bound) for the dynamic flow stress to use in crash simulations is

$$\sigma_p = \sigma_{0p} + 60 + 20 * \log \dot{\varepsilon}_p \quad \text{(MPa)} \qquad \text{equ. (4)}$$

For temper rolled materials (normally AISI 301 type) this estimate could also be used for true strains ≤ 5%. For higher strains of temper rolled stainless steel a strain rate independent value (the static flow stress) should be used.

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