VII International Conference on Computational Plasticity
COMPLAS 2003
E. Oñate and D. R. J. Owen (Eds)

CONSTITUTIVE MODELLING OF SANDVIK 1RK91

K. Datta, M. Hommes*, J. Post*, H. J. M. Geijselaers, H. Huétink and J. Beyer

The Netherlands Institute for Metals Research, Applied Mechanics Group, Department of Mechanical Engineering, University of Twente, 7500 AE Enschede, The Netherlands.

*Philips DAP B. V., Advanced Technology Centre, Building AX-24, P. O. Box 20100, Oliemolenstraat, 5, 9200 CA, Drachten, The Netherlands.

Key words: Constitutive Equation, Metastable Steels, Austenite, Martensite, Precision Forming

Abstract. *A physically based constitutive equation is being developed for the maraging stainless steel Sandvik 1RK91. The steel is used to make precision parts. These parts are formed through multistage forming operations and heat treatments from cold rolled and annealed sheets. The specific alloy is designed to be thermodynamically unstable, so that deformation even at room temperatures can bring about a change in the phase of face centred cubic austenite to either hexagonal closed packed martensite and/or, body centred cubic martensite. This solid state phase change is a function of the strain path, strain, strain rate and temperature. Thus, the fraction of the new phase formed depends on the state of stress at a given location in the part being formed. Therefore a set of experiments is being conducted in order to quantify the stress-strain behavior of this steel under various stress states, strain, strain rate as well as temperature. A magnetic sensor records the fraction of ferromagnetic martensite formed from paramagnetic austenite. A thermocouple as well as an infra red thermometer is used to log the change in temperature of the steel during a mechanical test. The force-displacement data are converted to stress-strain data after correcting for the changes in strain rate and temperature. These data are then cast into a general form of constitutive equation and the transformation equations are derived from Olson-Cohen type functions.*

—

1 INTRODUCTION

The deformation-induced martensitic transformation is assisted by an increase in tensile hydrostatic stress and hindered by an increase in compressive hydrostatic stress[1]. This phenomenon can be ascribed to assist the volume expansion due to the transformation from austenite to martensite. Therefore, in well defined homogeneous experiments like a tensile test or a compression test (upsetting), naturally, to generate an equal amount of martensite, more equivalent deformation is required during compression than during a tensile test[2]. But in reality, the steel is formed through a series of steps where the material flows in non-homogeneous manner and the state of stress could be tensile or compressive depending up on the loading, rate of loading, friction conditions, temperatures and therefore, it is a local variable within the bulk metal piece. Therefore, constitutive equations derived purely on a single set of homogeneous experiments like a tensile test or a compression test (upsetting) may not be sufficient to model the state of stress-strain and microstructural transformations in the operating zone (strain-strain rate and temperature) of the actual forming process. In this paper, a general method for deriving a physically based constitutive equation for a specific Cr-Ni maraging stainless steel is described. These equations are meant to be incorporated in large strain Finite Element Models of precision stamping process.

2 EXPERIMENTAL METHOD

The material of investigation is a cold rolled and annealed sheet of maraging stainless steel called Sandvik 1RK91. The chemical composition of this steel is given in Table 1. A change of phase takes place owing to deformation and typically, a paramagnetic austenite matrix transforms to a ferromagnetic martensite matrix. This change in phase during a tensile test is recorded with the help of a magnetic sensor (Fig. 1).

C, N	Cr	Ni	Mo	Ti	Al	Si	Cu
<0.05	12.0	9.0	4.0	0.9	0.30	0.15	2.0

Table 1: Chemical composition of Sandvik 1RK91 (weight percent)

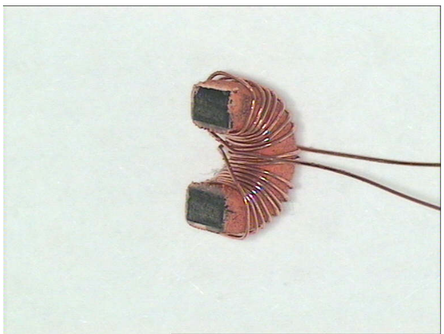


Fig. 1 The magnetic sensor used to measure the fraction of martensite phase

A set of tensile tests has been conducted covering a wide range of temperatures between –

50 °C and + 150 °C. The data considered for this study is taken between –50 °C and + 20 °C. The time, force, displacement, test temperature and the magnetic fraction formed are recorded with the help of a data acquisition system. The tested samples are subjected to various metallographic and X-Ray analyses.

3 RESULTS

Fig. 2 shows the experimental stress strain curves. It can be observed that the elongation to fracture diminishes with lowering of temperature. Also, lower the temperature, more prominent is the softening that occurs after the stress goes through a peak value. The extent of softening diminishes with rise in temperature.

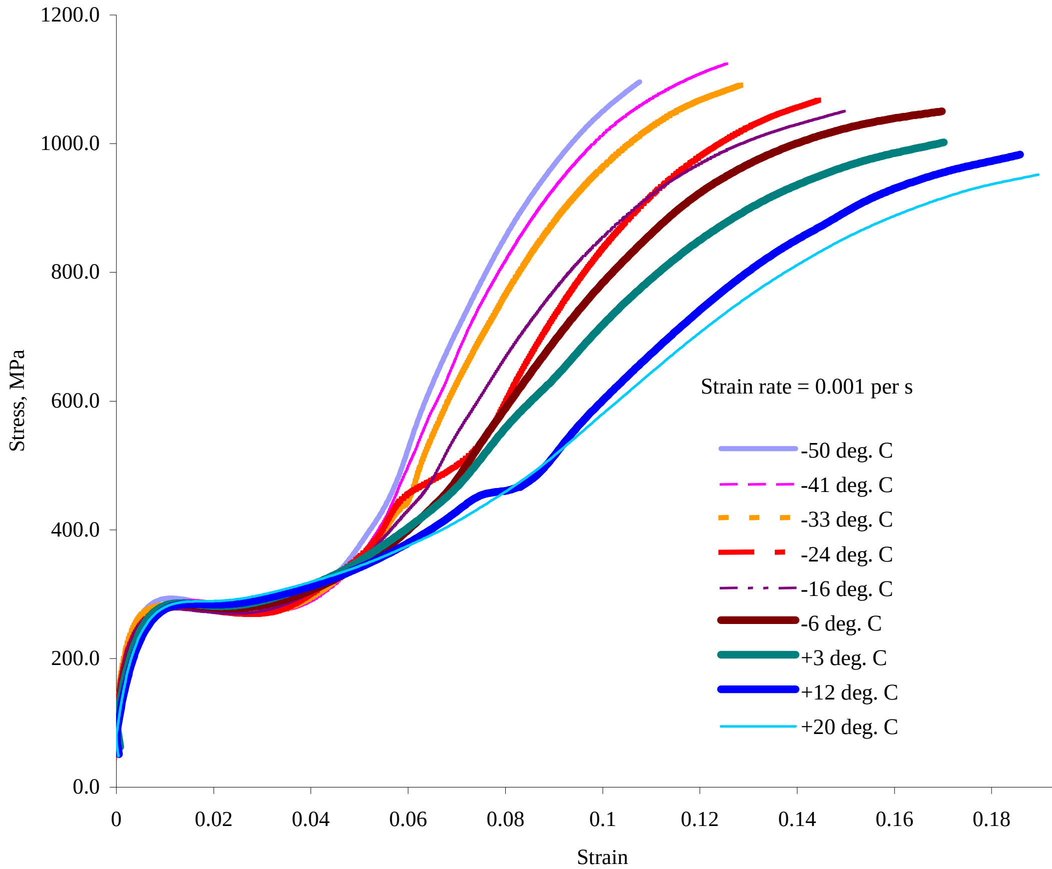


Fig. 2 Stress- strain curves for Sandvik 1RK91 obtained from tensile tests at various temperatures

Fig. 3 shows the corresponding curves for the fraction of deformation induced martensite formed. It can be observed that lower temperature favours the formation of martensite.

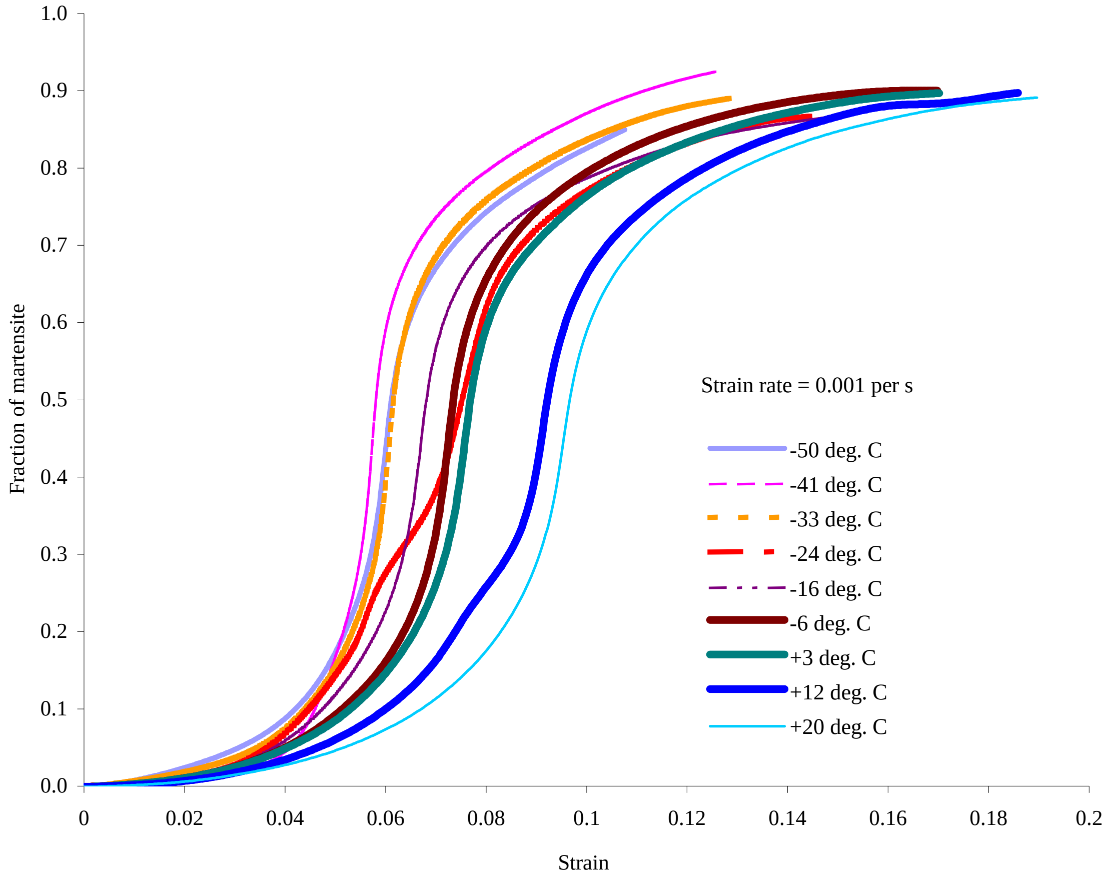


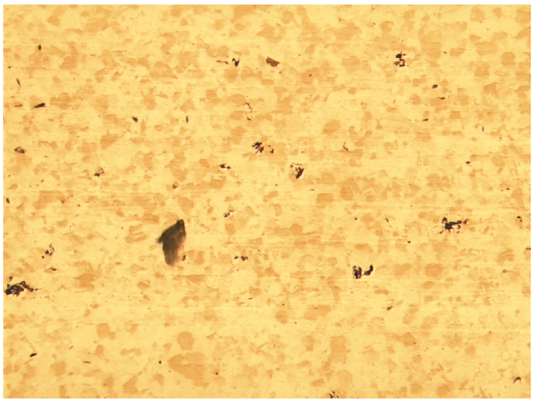
Fig. 3 Fraction of deformation induced martensite formed in Sandvik 1RK91 during tensile tests at various temperatures

Fig. 4 shows the micrographs, which demonstrate the progressive increase in the content of martensite with increase in strain.

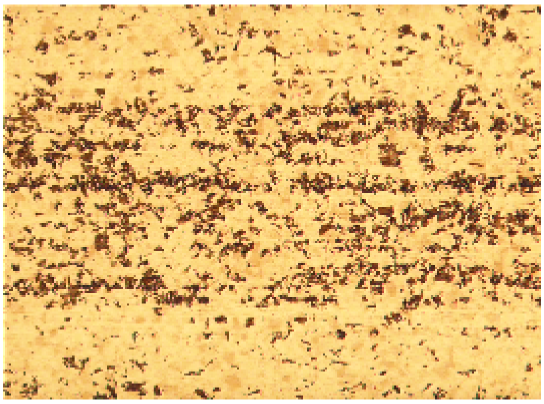
4 METHODOLOGY

4.1 Stress-strain equations

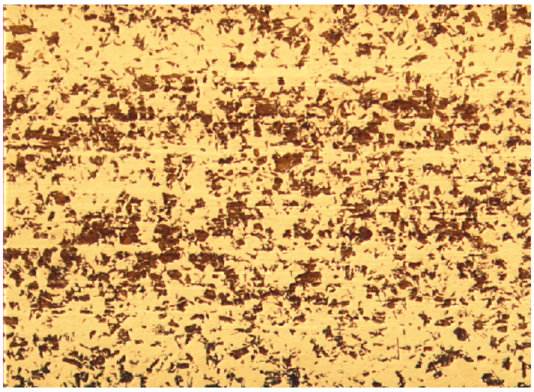
The constitutive equations are derived in two stages. The first stage equations are derived for discrete strains on the flow stress curve, which describe the stress at each of these points in terms of the Zener-Hollomon parameter, Z. In the second stage, equations describing continuous flow curves are derived, which use both the first stage equations and some additional information. A detailed description is mentioned in the two references[3,4]. Z is basically a temperature compensated strain rate, a parameter very relevant to hot deformation of metals. Hot forming of metals is typically rate sensitive. But cold forming, in general is not rate sensitive. However, a phase transformation driven by cold forming like austenite to martensite transformation is strain rate sensitive. Therefore, a parameter like Zener- Hollomon



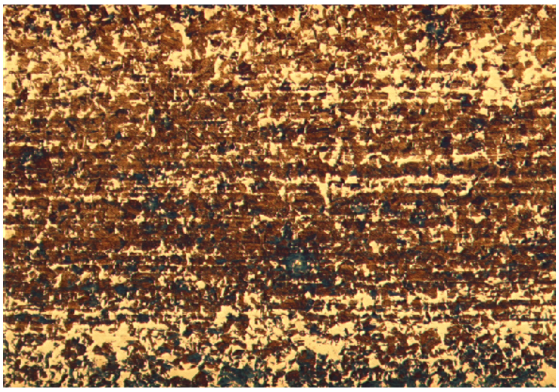
1% elongation



5% elongation



16% elongation



30% elongation

Fig. 4 Photomicrographs of a room temperature tensile test samples showing the growth of martensite phase with increase in elongation, magnification : x200

parameter can be conceptualised for the deformation of Sandvik 1RK91.

The effect of strain rate on strain induced martensite transformation has been studied previously[5-7]. Extensive hardening $(\frac{\partial \sigma}{\partial \varepsilon})$ is observed for lower strain rate and lower temperatures as these promote unstable austenite and faster martensite formation. Inhomogeneous flow in the actual work piece can produce a substantial increase in local strain rate. Therefore, tests at different strain rates are important. However, in this paper, constitutive equations are derived for tests conducted at a nominal and average rate of 0.001 s^{-1}. A schematic diagram of a typical stress strain curve for metastable austenitic stainless steel is given in **Fig. 5**. Some characteristic points are marked. These are stress σ_0 at strain ε_0 =0, $\sigma_{0.005}$ at strain $\varepsilon_{0.005}$ =0.005, σ_{peak} at ε_{peak} =peak strain, σ_{min} at strain ε_{min} = minimum strain, $\sigma_{ss(e)}$ at strain of $\varepsilon_{ss(e)}$ = steady state extrapolated strain. For each of these characteristic states, a relationship between σ and Z is found out. An equation that is valid over the entire range of

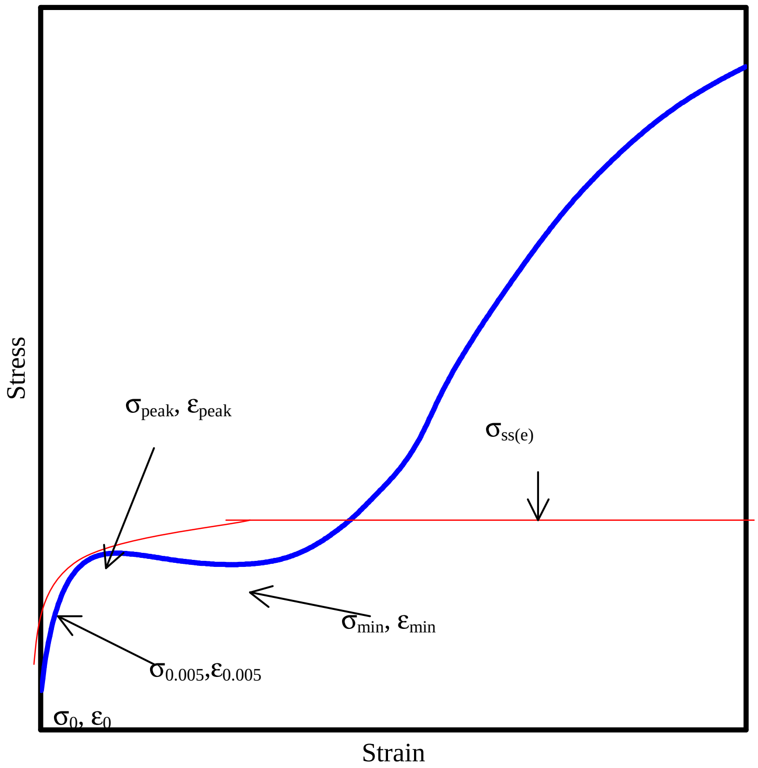


Fig. 5 A schematic diagram showing the characteristic points on

stresses, approximating to a power law at low stresses and to an exponential law at high stresses, is the hyperbolic sine relationship[8].

$$Z = A[\sinh(\alpha\sigma)]^n \quad (1)$$

$$\text{where } Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \quad (2)$$

Here $\dot{\varepsilon}$ is the strain rate, Q is the activation energy for concurrent deformation and phase transformation, R is the universal gas constant and T is the temperature. In order to obtain, the steady state extrapolated stress, $\sigma_{ss(e)}$, Kocks-Mecking plot[9] is constructed with each of the test data. Fig. 6 shows a typical Kocks-Mecking plot from where the peak, minimum as well as the extrapolated stresses can be worked out. After having found all the characteristic points for every stress-strain curve, the data are fitted to obtain the constants in equation (1). Table 2 gives a comprehensive summary of these constants. It is observed that there are two distinct zones of temperature where the material behaviour differs and hence, these constants are

Temperature regime	Characteristic state of strain	n	α	A
-50 °C to – 10 °C	0	1.0465	8.6001E-09	0.020644631
	0.005	5.1341	3.89552E-09	0.015444536
	peak	6.4682	3.09205E-09	0.026129247
	minimum	12.399	4.03258E-09	0.16434293
	extrapolated	-0.9793	3.06341E-09	0.024637145
-10 °C to +20 °C	0	1.0465	8.6001E-09	0.020644631
	0.005	5.1341	3.89552E-09	0.015444536
	peak	-8.2047	6.09407E-09	0.002518479
	minimum	-5.9002	5.08457E-09	0.780281911
	extrapolated	-6.8071	2.93811E-09	0.025341802

Table 2 The constants in equation (1) pertaining to different characteristic states for Sandvik 1RK91

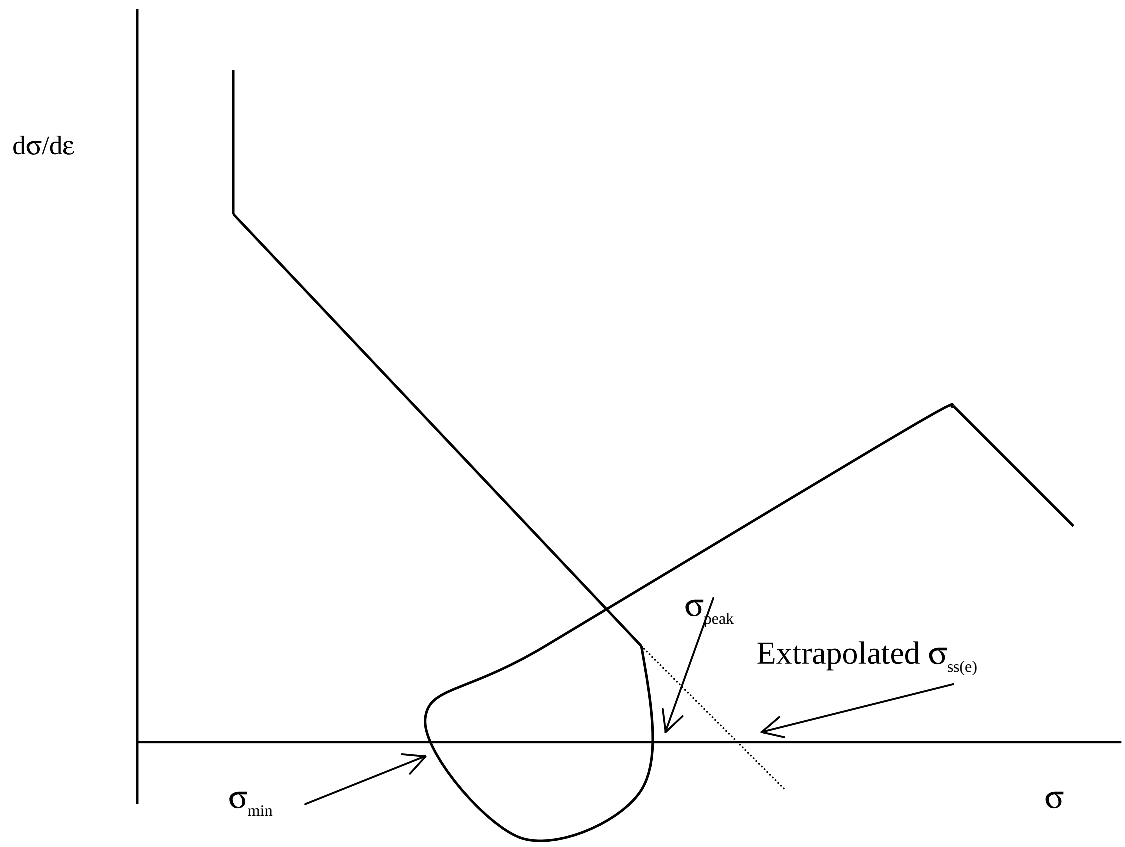


Fig. 6 Schematic differential isothermal flow stress curve for steels showing extrapolation for $\sigma_{ss(e)}$

derived separately, for each zone : a low temperature regime between –50 °C and –10 °C and a higher temperature regime between –10 °C and 20 °C. The first stage of equations developed so far define a set of discrete points on the flow stress curve, therefore the next stage, as stated earlier, is to develop a set of equations which describe continuous curves in terms of Z and ε. This is done in two steps.

(i) by describing the extrapolated curve, which would have been achieved, had the material not softened and reached a steady state of stress.

(ii) By subtracting the effect of dynamic softening and then hardening, from the extrapolated curve.

The extrapolated curve is defined by the following equations.

$$\sigma = \sigma_0 + (\sigma_{ss(e)} - \sigma_0)[(1 - \exp(\frac{\varepsilon}{\varepsilon_r})]^{\frac{1}{2}} \quad (3)$$

where,

$$\varepsilon_r = -0.1(\ln\{1 - [(\sigma_{0.005} - \sigma_0)/(\sigma_{\min} - \sigma_0)]^{\frac{1}{m}}\}) \quad (4)$$

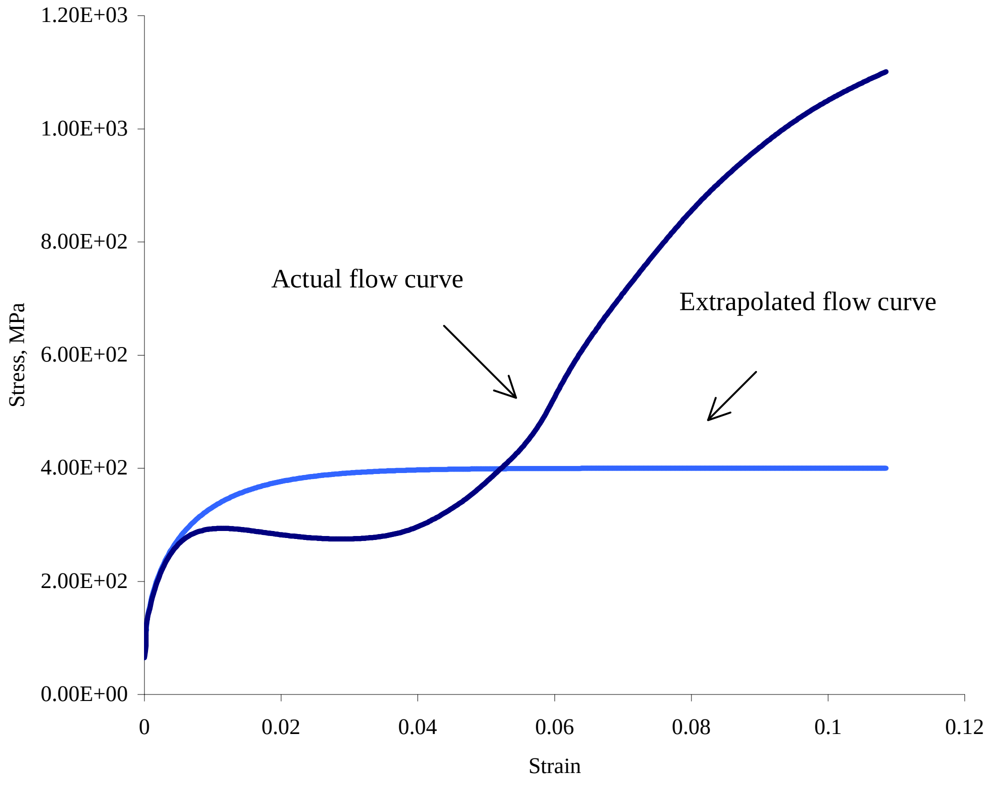


Fig. 7 Comparison of typical experimental and extrapolated flow stress curves derived as demonstrated in Figs. 5 and 6.

In practice, the value of ε_r is found through a fitting process. Fig. 7 shows a comparison of typical experimental and extrapolated flow stress curves derived as demonstrated in Figs. 5

and 6. Once the extrapolated flow curve has been modeled, it is then possible to subtract from it the effect of softening and then the subsequent hardening, by using an equation of the form

$$\Delta\sigma = \Delta\sigma_{\min}(1-\exp\{-[(\varepsilon-\varepsilon_p)/(\varepsilon_{xr}-\varepsilon_p)]^p\}) \qquad (5)$$

The unknown quantities p and ε_{xr} can be obtained by fitting the majority of the data, allowing for the end effects on the data.

4.2 Equations for the fraction of martensite formed

The Olson-Cohen[10] relationship for martensite formation is used to fit the experimental data

$$f_m = 1-\exp\{-\beta'[1-\exp(-\alpha'\varepsilon)]^{n'}\} \qquad (6)$$

The transformation curve is thus defined by two physically significant parameters α′ and β′ and an exponent n′. **Table 3** describes the relationship of these parameters to temperature, as obtained by fitting to the experimental data.

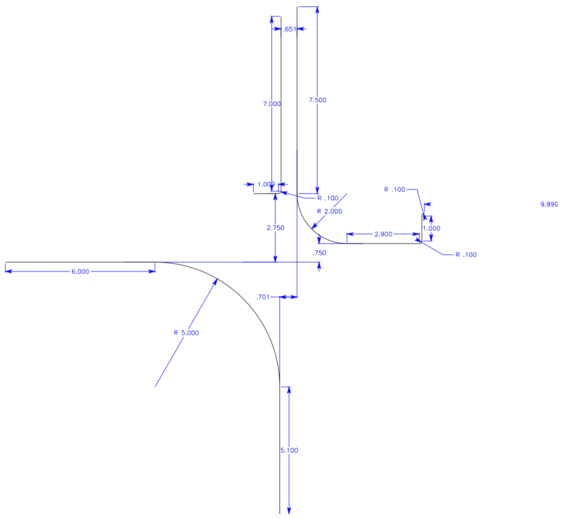
Temperature regime	α	β′	n′
-50 °C to –10 °C	-0.0874 $(T+273)^2$ +40.322 (T+273) - 4583	2.19	-2.7388 (T+273) + 696.59
-10 °C to +20 °C	0.013 $(T+273)^2$ -7.5812 (T+273) + 1139.8	2.19	0.0017 $(T+273)^3$ – 1.3567 $(T+273)^2$ + 362.01 T - 32110

Table 3 The constants in equation (6) for the fraction of martensite formed in Sandvik 1RK91

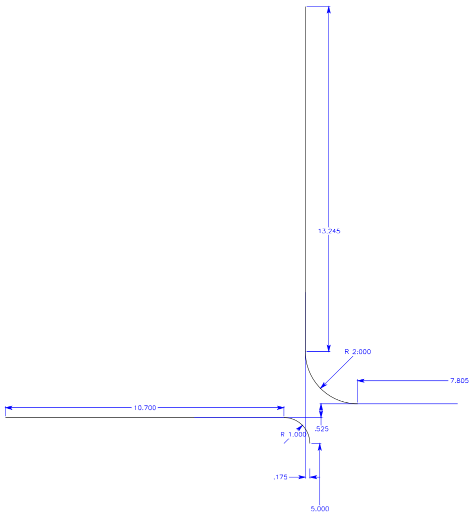
5 APPLICATION

The constitutive equations and transformation relationships are derived under different states of stress as well as strain rate and temperatures. These equations are derived for each state of stress (like pure shear, or pure compression, or pure tensile, as in this paper). In a Finite Element model, these equations are input to the material model. An algorithm is currently being worked out on how best to apportion these equations because, a material point could simultaneously have any combination of shear, compressive and tensile state of stress in the three dimensions and the three planes. Here, an example calculation is shown where the

Step 1



Step 2



Step 3

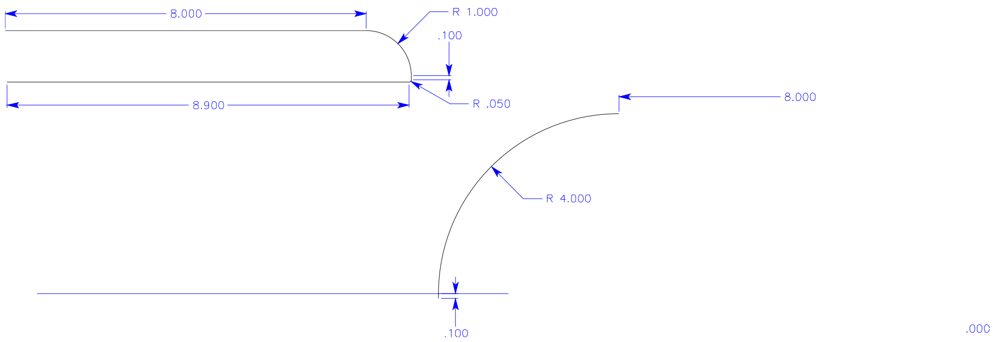


Fig. 8 Drawings of the positions of the dies with respect to the blank for the three step stamping process called TIMPLE

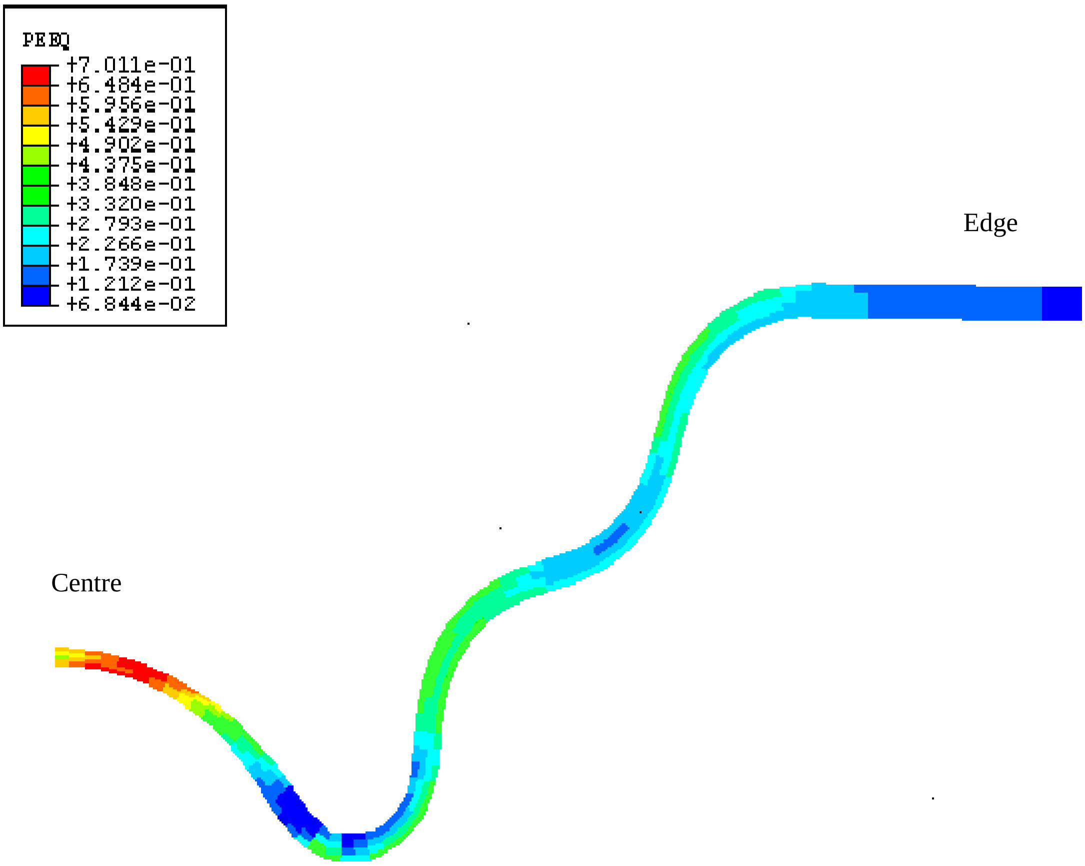


Fig. 9 Contour plot of the equivalent plastic strain in Sandvik 1RK91 which develops after the third step of stamping during a TIMPLE process

equations derived from the tensile tests are used to model a three step stamping operation called TIMPLE[11]. So here it is assumed that the rate of phase transformation during biaxial stretching is the same as that during tensile loading. Fig.8 Shows the three step stamping process TIMPLE and Fig.9 is a contour plot of the equivalent plastic strain that develops after the last step of stamping. These simulations are carried out using the internal Finite Element code of Philips as well as ABAQUS 6.3. Once constitutive equations for every state of stress are available, they will be included in the model, such that a more realistic state of strain, strain, temperature and fraction transformed can be computed.

6 DISCUSSION

The formulation of constitutive behaviour with the help of Zener-Hollomon parameter proves to be effective in describing the concurrent deformation and transformation behaviour of metastable stainless steels. However, tests with varying strain rates should be included to bring out the effect of strain rate on transformation and flow behaviour of the steel. The parameter n' in the transformation equation is supposed to be a constant, but for 1RK91, it is found to be varying with the temperature. On the contrary, parameter β' is found to be a constant, which is supposed to be a temperature-dependent parameter[10]. α' defines the course of shear band formation with strain and depends on the stacking fault energy. β' is related to the chemical driving force that an embryo of martensite would be formed. Therefore, the transformation kinetics needs further study to overcome these ambiguities.

These tests were carried out with thermocouple recording the average test temperature. However, for a precise calculation of the activation energy as well as enthalpy of phase transformation, an accurate temperature measurement of the test piece itself is necessary. Such data would refine the constitutive equations considerably. X-ray and other metallographic analyses are underway to know the microstructural phenomenon that causes softening in the flow curves, very similar to dynamic recrystallisation during hot forming of metals.

7 CONCLUSION

A methodology for generating constitutive equations, which is more commonly known to hot deformation of metals, has been effectively applied to a meta stable alloy system. This method has a strong physical basis since it accounts for the dynamic softening and hardening which occur during deformation and it provides a quantitative description to these phenomena.

8 ACKNOWLEDGEMENTS

The authors would like to thank Mr. H. Nolles of Philips DAP, Advanced Technology Centre for developing the magnetic sensor. They are also thankful to Mr. Richard Jousma, graduate student at the University of Twente, for a part of the regression analyses. They are also very grateful to Netherlands Institute for Metals Research and Philips B.V. for the permission to publish this work.

REFERENCES

[1] Matsuo USUDA, Shunji HIWATASHI, Koji SAKUMA, Tomohisa KATAYAMA and Manabu TAKAHASHI, Journal of the Japanese Society for Technology of Plasticity, vol.**39**, No.444,January 1998.

[2] T. van Amstel, Report no. ASB 53.1 – 1230, Philips Domestic Appliances and Personal Care B.V., April 9, 2001

[3] K. Datta, "Finite Element Modelling of Hot Rolling", Ph. D. Thesis, The University of Sheffield, 1996.

[4] S. B. Davenport, N. J. Silk, C. N. Sparks and C. M. Sellars, Materials Science and Technology, May 2000, vol. **16**, 539 – 546.

[5] M. Azrin, G. B. Olson and R. A. Gagne, Materials Science and Engineering, vol. **23**, 1976, 33 – 41.

[6] S. S. Hecker, M. G. Stout, K. P. Staudhammer and J. L. Smith, Met. Trans. vol. **13A**, April 1982, 619 – 626.

[7] *Ibid*, 627 – 635.
[8] C. M. Sellars and W. J. McG. Tegart, Mem. Sci. Rev. Metall., 1966, vol. **63**, 731 – 746 (in French).
[9] Y. Estrin and H. Mecking, Acta Metall., 1984, vol. **32**, 57 – 70.
[10] G. B. Olson and M. Cohen, Met. Trans. A, vol. **6A**, April 1975, 791 – 795.
[11] J. Post, J. Huétink, H. J. M. Geijselaers, R. M. J. Voncken, “FEM simulations of a multi stage forming process on Sandvik maraging steel 1RK91 describing the stress assisted and the strain induced martensite transformation”, a paper presented at ICOMAT02, June 10 – 14, 2002, Helsinki University of Technology, Espoo, Finland.