A DACE study on a three stage metal forming process made of Sandvik Nanoflex™

J. Post*, G. Klaseboer*, E. Stinstra† and J. Huétink**

*Philips DAP/ATC, P.O. box 20100, 9200 CA Drachten, The Netherlands
†CQM, P.O. box 414, Eindhoven, The Netherlands
**NIMR, University of Twente, Department of Mechanical Engineering, P.O. Box 217, 7500 AE Enschede, The Netherlands

Abstract. Sandvik Nanoflex™ combines good corrosion resistance with high strength. The steel has good deformability in austenitic conditions. This material belongs to the group of metastable austenites, so during deformation a strain-induced transformation into martensite takes place. After deformation, the transformation continues as a result of internal residual stresses. Depending on the heat treatment, this stress-assisted transformation is more or less autocatalytic. Both transformations are stress-state, temperature and crystal orientation dependent.

This article presents a constitutive model for this steel, based on the macroscopic material behaviour measured by inductive measurements. Both the stress-assisted and the strain-induced transformation to martensite are incorporated in this model. Path-dependent work hardening is also taken into account, together with the inheritance of the dislocations from one phase to the other. The model is implemented in an internal Philips code called CRYSTAL for doing simulations. A multi-stage metal forming process is simulated. The process consists of different forming steps with intervals between them to simulate the waiting time between the different metal forming steps.

During the engineering process of a high precision metal formed product often questions arise about the relation between the scatter on the initial parameters, like standard deviation on the strip thickness, yield stress etc, and the product accuracy. This becomes even more complex if the material is:

- instable,
- the transformation rate depends on the stress state, which is related to friction,
- the transformation rate depends on the temperature, which is related to deformation heat and the heat distribution during the entire process.

A way to get more understanding in these phenomena in relation to the process is doing a process window study, using DACE (Design and Analysis of Computer Experiments). In this article an example is given how to make a DACE study on a a three stage metal forming process, using a distributed computing technique. The method is shown, together with some results. The problem is focused on the influence of the transformation rate, transformation plasticity and dilatation strain on the product accuracy.

THE MATERIAL MODEL FOR SANDVIK NANOFLEX™

Sandvik Nanoflex™ belongs to the category of metastable austenitic stainless steels. It is also a precipitation hardenable steel, which means that the martensite phase can be aged [1, 2]. For the chemical composition, see Table 1.

Depending on the stability of the steel, two phenomena occur:

- a stress-assisted transformation, below the flow stress of the composite,
- a strain-induced transformation, above the flow-stress of the composite at higher temperatures above the martensite start temperature M_s^σ.

These transformations are stress state and temperature dependent.

Strain-induced transformation

The following equation is used to describe the strain-induced transformation:

$$\dot{\varphi}_{\text{strain}} = C_{\text{strain}}(T, \sigma^{\text{H}}, Z)[(D_1 + \varphi)^{n_1}(f - \varphi)^{n_2}]\dot{\varepsilon}^{\text{p}}, \quad (1)$$

where φ is the martensite content and C_{strain} is a function that describes the dependence of the transformation on the temperature T, hydrostatic stress σ^{H} and material

CP712, *Materials Processing and Design: Modeling, Simulation and Applications,* NUMIFORM 2004,
edited by S. Ghosh, J. C. Castro, and J. K. Lee

TABLE 1. Chemical composition of Sandvik Nanoflex™ steel[1]

	C+N	Cr	Ni	Mo	Ti	Al	Si	Cu
Nanoflex™	≤0.05	12.0	9.0	4.0	0.9	0.40	≤0.5	2.0

structure Z. The parameter Z depends on the annealing conditions before metal forming, the chemical composition and crystal orientation and is treated as a constant for this study, C_{strain} is related to the thermodynamics of the transformation.

In Figures 1 and 2, the simulated and measured flow stress and martensite content are depicted as function of the equivalent plastic strain . The values n_1 and n_2 are fit constants, D_1 is related to the nucleation of the transformation and f is the saturation value of the transformation. In both figures, the far left lines correspond to a temperature of 223 K whereas the far right lines correspond to 423 K.

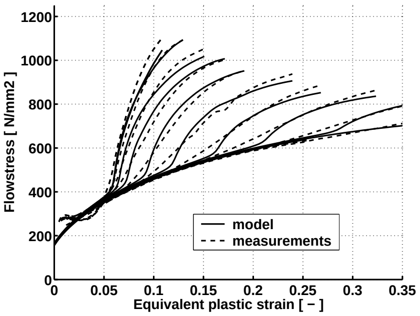

FIGURE 1. The fitted flow stress model and measured data.

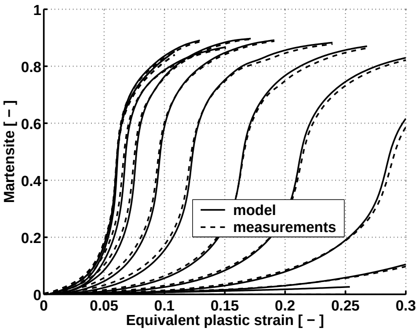

FIGURE 2. The fitted strain-induced martensite model and measured data.

Stress-assisted transformation

The description of the stress-assisted transformation is based on [3], but rewritten in a more general form:

$$\begin{aligned}\dot{\varphi}_{\text{stress}} = & C_{\text{stress}}(T,\sigma^{\text{H}},\varepsilon^{\text{p}},Z)[(D_2(Z)+\varphi)^{n_3} \\ & (f_{\text{stress}}(T,\sigma^{\text{H}},\varepsilon^{\text{p}},Z)-\varphi)^{n_4}],\end{aligned} \tag{2}$$

where C_{stress} is a function that describes the dependence of transformation on hydrostatic stress, temperature and material structure. Figure 3 shows the stress- assisted transformation after plastic pre-straining (resulting in 50% martensite), as function of the imposed stress level. For the total martensite applies:

$$\dot{\varphi} = \dot{\varphi}_{\text{stress}} + \dot{\varphi}_{\text{strain}}, \tag{3}$$

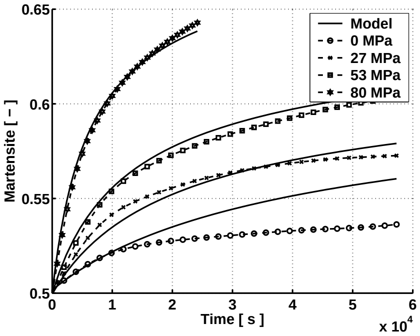

FIGURE 3. Stress assisted transformation as function of imposed stress level, after plastic pre-straining up to a martensite content of 50%

Work hardening

For this study it is assumed that the work hardening depends on plastic strain, martensite content, temperature, and the influence of strain rate. The flow stress of austenite ($i = 1$) and martensite ($i = 2$) is written as:

$$\sigma_i^{\text{Y}} = \sigma_{0_i}\sqrt{Y_i}\left(1+\frac{\dot{\varepsilon}^{\text{p}}}{\psi_i}\right)^{\frac{1}{m_i}}, \tag{4}$$

Here, σ_0 is the basic stress which depends on strain rate and temperature, Y is the general dislocation density for one phase, $\dot{\varepsilon}_p$ is the equivalent plastic strain rate, ψ the reference strain rate and m a constant depending on strain rate and temperature. For the combination of both phases the equation becomes

$$\sigma^{\text{Y}} = \sigma_1^{\text{Y}} + \frac{1+\tanh\left(\frac{\varphi-\varphi_0}{q}\right)}{2}(\sigma_2^{\text{Y}}-\sigma_1^{\text{Y}}), \tag{5}$$

where φ_0 and q are introduced to describe the non-linear relation between the flow stresses as a mixture rule. The evolution of the dislocation density in the austenite and martensite is described as follows:

$$\dot{Y}_i = \begin{cases} [C_{1i}(C_{2i}-Y_i)^{C_{3i}} + C_{4i}(\dot{\varepsilon}^{\mathrm{p}}, T)]\,\dot{\varepsilon}^{\mathrm{p}} & \text{if } Y_i \le C_{2i}, \\ [C_{4i}(\dot{\varepsilon}^{\mathrm{p}}, T)]\,\dot{\varepsilon}^{\mathrm{p}} & \text{if } Y_i > C_{2i}, \end{cases} \tag{6}$$

where C_{1i}, C_{2i}, C_{3i} are material constants and C_{4i} depends on temperature and strain rate. The constants are not directly related to physical phenomena but are chosen to fit the experiments.

To describe the recovery effect for the dislocation transfer during transformation the following equation is introduced:

$$\dot{Y}_2^{\mathrm{trans}} = \frac{\dot{\varphi}_{\mathrm{strain}}}{\varphi_{\mathrm{strain}}}(C_9(T)Y_1 + C_{10}) - \frac{\dot{\varphi}}{\varphi}Y_2, \tag{7}$$

where C_9 is a constant that depends on temperature and C_{10} depends on the transformation boundary. For more details on the model, the reader is referred to [4].

PROCESS WINDOW STUDIES

Introduction

The ever increasing pressure on the development time of new products and processes has changed the design process over the years drastically. In the past, design merely consisted of experimentations and physical prototyping. In the last decade, computer simulation models such as FEM and CFD have become very popular in engineering design and analysis. The application described in this paper is just one of many examples. In many cases, only predicting the quality characteristics of a design is not enough. Usually, designers are confronted with the problem of finding settings for a number of design parameters that are optimal with respect to several simulated product or process quality characteristics.

Since there are usually many possible combinations of design parameter settings, the crucial question becomes how to find the best possible settings with a minimum number of simulations. This new challenge has led to a new engineering discipline, often referred to as design and analysis of computer experiments (DACE). All methodologies that are suggested in literature rely heavily on statistics and mathematical optimization theory. Generally, we can distinguish two types of approaches: iterative approaches and global modelling approaches. Many papers have been published on applications of DACE in a wide variety of engineering disciplines. In this paper, we present, with the DACE method Compact [5], an application on optimizing the manufacturing process. Compact has already been used in several cases, for example see Den Hertog and Stehouwer[5], and is based on global modelling , see Figure 4.

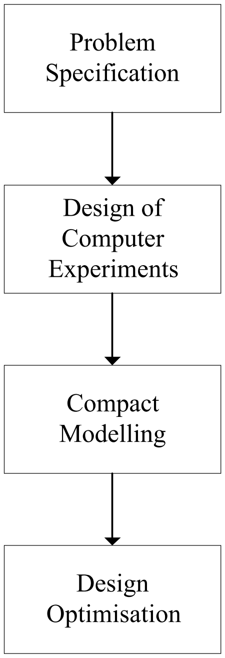

FIGURE 4. The Compact approach.

DISTRIBUTED COMPUTING

Distributed computing is based on using the idle computing time within computer networks, by doing defined tasks within this time period. The design choices that were made concerning, the structure and the protocols to build the distributed system, are based on the scalability, robustness and controllability of the system.

The entire process is monitored and controlled through the use of three databases see Figure 5:

- the user database,
- the calculation database,
- the client database.

The user database is coupled to the calculation database and contains information about the users. The client database contains information about the clients such as: number of calculations done, computer architecture and calculations being computed. The client database is also coupled to the calculation database. The calculation database contains the information about the calculation such as: calculation-id, status, calculation type, calculation size and owner.

TABLE 2. Used parameters in DACE analyses, *: 1=normal, 2=uniform

Number	Parameter	Low	High	Dimension	Distribution*	3 * Std. deviation
1	Initial temperature	288	298	K	1	5
2	Material thickness	0.49	0.51	mm	1	0.01
3	Influence Chemical composition (C_{strain})	280	420	K	1	25
4	Initial flow stress austenite	280	380	N/mm^2	1	50
5	Saturation value for martensite (f_{stress})	0.6	0.8	-	1	0.1
6	Time step between step1 and step2	0	600	sec	2	300
7	Time step between step2 and step3	0	600	sec	2	300
8	Waiting time after step3	100	10800	sec	2	5100
9	Ram depth step1 related to nominal	-0.02	+0.02	mm	1	0.02
10	Ram depth step2 related to nominal	-0.02	+0.02	mm	1	0.02
11	Ram depth step3 related to nominal	-0.02	+0.02	mm	1	0.02
12	Coulomb Friction	0.008	0.15	-	1	0.035

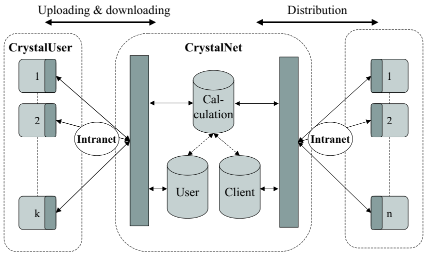

FIGURE 5. The structure of the CRYSTAL distributed computing system.

The example process

The example product is a stamped and hardened axisymmetric product made of Sandvik Nanoflex™ [6], see Figure 6. The product is stamped in three metal forming steps and a heat treatment. The total production process consists of different steps:

- 1: stamping step: a simple deep drawing operation,
- 2: waiting step which simulates the transport of the product from stamping step 1 to 2,
- 3: stamping step, a second deep drawing step,
- 4: waiting step, simulating the transport from stage 2 to stage 3,
- 5: stamping step: biaxial stretching in reverse direction,
- 6: waiting step: this is the time from stamping up to austenitising,
- 7: austenitising during 30 minutes at 1373 K, During this austenitising the material becomes instable,
- 8: an isothermal transformation step at 223 K during 24 hours,
- 9: precipitation step during 15 min at 823 K.

During the stamping process the product will become partly martensitic, during waiting this transformation continues. After austenitising, the product is fully austenitic and during isothermal transformation it will become martensitic again on a level of about 60 to 80%. During this transformation process, transformation and dilatation strains will occur, resulting in dimensional changes of the product shape.

The aim of this example is to look at the Hardness and the accuracy of the bearing radius on the top of the product, see figure 6. The question to solve is:

- What is the best product route to realize the most accurate radius and a high hardness.

An extra problem is that Sandvik Nanoflex™ has a stress assisted transformation after stamping, related to the residual stresses caused by stamping. This results in dimensional changes after stamping in time, this waiting is a part of the simulation.

FIGURE 6. A photo of the three stage process.

TABLE 3. Nominal values of the response parameters

Hardness	Radius
$450HV(0.2)$	$4.1mm$

CALCULATIONS

The Compact approach consists of 4 steps, see also Figure 4:

- problem definition: In the first step, the design analyses problem is defined. First of all, we need to define the design parameters that we want to vary, see Table 2. Next, we need to define the quality characteristics that are important in evaluating the process. These quality characteristics are usually referred to as response parameters. In this case, response parameters are divided over three process steps. For every step, we defined the response parameters that are printed in Table 3,
- Design of computer experiments: The second step in the Compact methodology generates a set of suitably chosen combinations of design parameter settings or design points that must be located within the feasible design region, i.e., the part of the design parameter space that satisfies all bounds on design parameters defined in step 1, using so-called Latin Hypercube Designs (LHD) approach [5],
- Compact modelling: The third step consists of fitting a compact model for every response parameter in terms of the design parameters. There are three types of models: linear, quadratic and interpolation models such as Kriging models. The compact models are based on the simulation output generated after step 2. After models are fitted, they are validated to see if their predictions are accurate enough. If not, extra simulation results are added to the compact models. In this case it consists of 120 X 7(number of steps) calculations, solved using a distributed computing technique with a LAN consisting of 30 CPU’s. All calculations were done within 100 hours, total CPU time 3000 hours.
- Analysis: Since in this process window study we want to find out how sensitive the design is to variations in the (in reality non-controllable) design parameter settings, we defined a realistic probability distribution on the design parameters. Since compact models can be evaluated very quickly in comparison to the simulation, we can use a Monte Carlo study (which uses thousands of evaluations) to analyse the effect of the from probability distribution on the response parameters. In this way we analyse the robustness of the process.

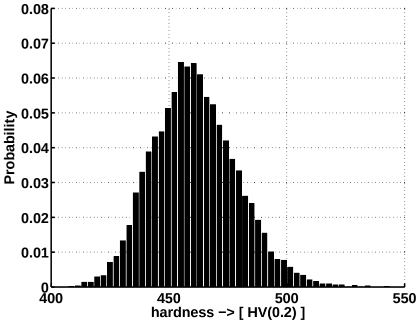

FIGURE 7. The hardness distribution after stamping.

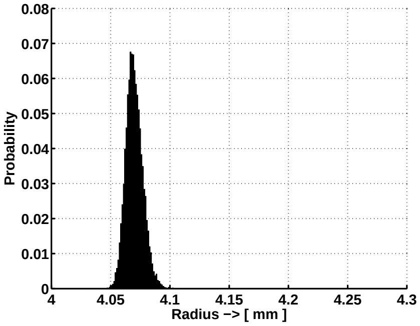

FIGURE 8. The radius distribution after stamping.

RESULTS

The results of three Monte Carlo simulations are shown in the following figures:

- Figure 7 and 8 give the results direct after stamping,
- Figure 9 and 10 give the results after stamping and waiting for 10800 sec. It is assumed that after

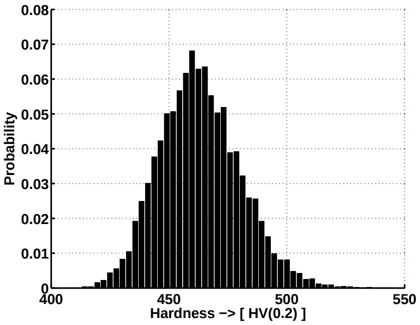

FIGURE 9. The hardness distribution after stamping and waiting for 24 hours stamping.

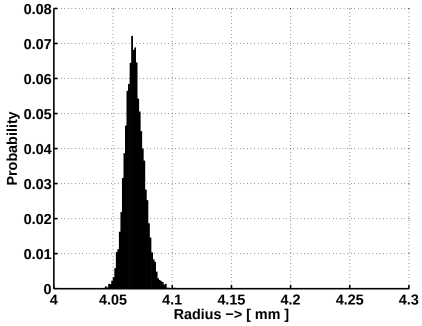

FIGURE 10. The radius distribution after stamping and waiting for 24 hours stamping.

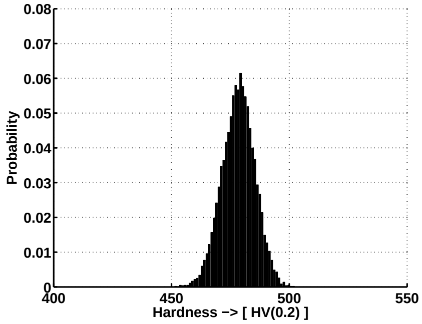

FIGURE 11. The hardness distribution after stamping, waiting and re-hardening.

this time the stress-assisted transformation stops because the positive residual stress will vanish due to the dilatation strain. The results are very similar with the results after stamping but there are some little dimensional changes,

- Figure 11 and 12 give the results after stamping, waiting, re-austenising and isothermal hardening. The graphs show that using this method the hardness will increase, but the accuracy of the radius will decrease. This is related to the dilatation and strain and transformation plasticity.

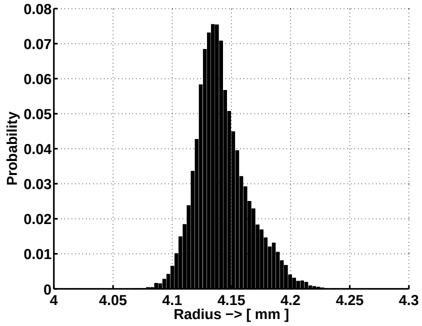

FIGURE 12. The radius distribution after stamping, waiting and re-hardening.

CONCLUSIONS

- DACE is a powerful instrument in combination with a robust FEM solver to get inside information on a process window,
- The most accurate product is realized by using only the strain induced hardening and aging process,
- The highest hardness is realized by using the re-austenizing and isothermal hardening and aging process.

ACKNOWLEDGMENT

This work was carried out in cooperation with the Netherlands Institute for Metals Research (NIMR).

REFERENCES

1. M. Holmquist, J.-O. Nilsson, and A.H. H. Stigenberg. Isothermal formation of martensite in a 12cr-9ni-4mo maraging stainless steel. *Scripta Metallurgia et Materialia*, January 1995.
2. J.-O. Nilsson, A.H. H. Stigenberg, and P. Liu. Isothermal formation of quasicrystalline precipitates and their effect on strength in a 12cr-9ni-4mo maraging stainless steel. *Metallurgical and Materials Transactions A*, 25A:2225–2233, October 1994.
3. v. Raghavan. Kinetics of martensite transformtions in the book martensite, edited by g.b.olson and w.s. owen. (ISBN 0-87170-434-X):197–225, 1992.
4. J. Post. Constitutive behaviour of the metastable stainless steel: Sandvik Nanoflex™ . *This conference*, 2004.
5. P. Stehouwer D.den Hertog. Simulation-based design optimisation: Methodology and applications. *ASMO UK/ISSMO*, 1999.
6. R.M.J. Voncken. Fe calculations on a three stage metal forming process of sandvik Nanoflex™ . *This conference*, 2004.