

Coating-substrate-simulations applied to HFQ[®] forming tools

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Abstract. In this paper a comparative analysis of coating-substrate simulations applied to HFQTM forming tools is presented. When using the solution heat treatment cold die forming and quenching process, known as HFQTM, for forming of hardened aluminium alloy of automotive panel parts, coating-substrate-systems have to satisfy unique requirements. Numerical experiments, based on the Advanced Adaptive FE method, will finally present.

1. Introduction

Aluminium alloys suffer from low ductility and have a tendency to springback by up to 30% after cold forming or post-forming heat treatment, used after hot stamping, meaning that the materials partly revert to their original shape. A technique called solution-heat treatment, forming and cold-die quenching (HFQ[®]) [1] can alleviate this problem. The conventional approach for processing aluminium alloys involves three stages – forming the part, carrying out a solution heat treatment and then aging the part. Whatever sequence the first two processes are carried out in, there is an adverse impact on the alloy. If the heat treatment is carried out before the forming process, the alloy becomes difficult to form, whereas if the forming process comes first, the rapid cooling of the part during post-heat treatment can cause distortions. In the patenting process [2] the heat treatment and forming process are combined in one operation. In the die are cooling channels in order to keep the die temperature low. If the die temperature is too high, there is no rapid cooling and for aluminium alloys, this is a very sensitive issue. If there is no rapid cooling, then you may get precipitates forming at grain boundaries, and so the microstructure is affected and then cracking can take place too readily. The approach is said to almost completely inhibit spring back, enabling part shape and microstructure to be controlled more easily for larger and accurate panels, with improved strength of up to 25% [3].

2. Special demands on coating-substrate-systems on forming tools for HFQ[®]

One of the most critical process parts for HFQ[®] is the quenching process (Fig. 1).

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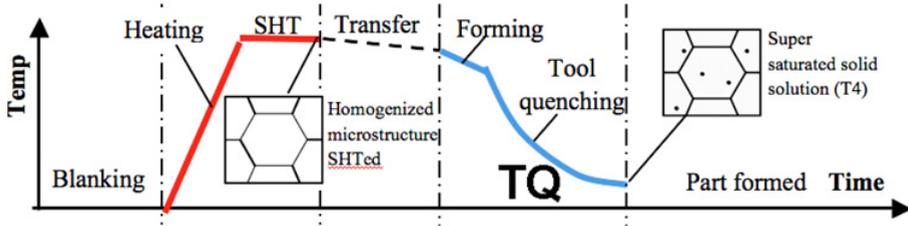


Figure 1. Critical part (TQ) at the HFQ[®] process [4].

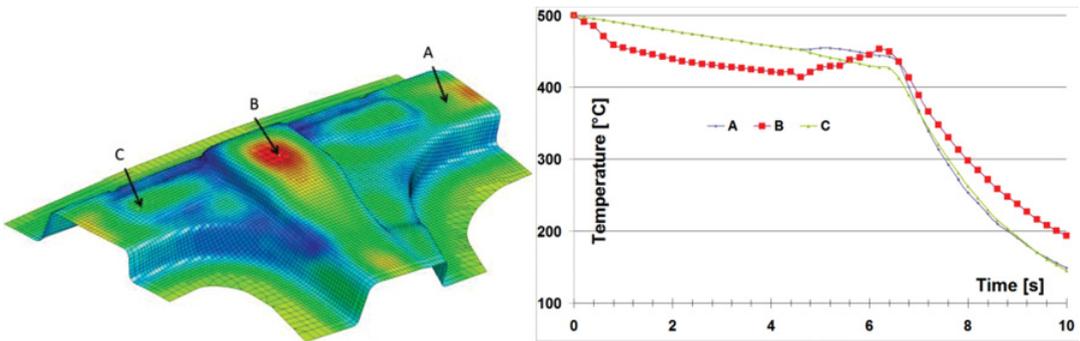


Figure 2. Temperature distribution within the forming sheet.

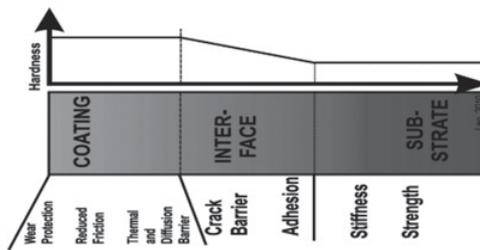


Figure 3. Coatings.

As a result of a forming simulation (Fig. 2) for an aluminium sheet, it could be find out, that the restricted cooling time can be realized with cooling of the forming tool and with high thermal conductivity between the aluminium sheet and the forming tool itself.

As known from other forming operations, there are a few spots for high mechanical and thermal loading at the tool (B in Fig. 2). In addition to the well-known typically requirements for coatings given in Fig. 3, thermal properties like thermal conductivity, thermal expansion, specific heat capacity and friction conditions are of particular importance.

3. Selected coating-substrate-systems

For hot forming tools the high vanadium content steel H13 with increased resistant to heat checking (below 650 °C) and abrasive wear are widely used. H13 appears to have good thermal-shock resistance and can be water cooled [5]. To reduce overall manufacturing costs, one alternative for the expensive

Table 1. Used material properties [15].

Material	Modulus of Elasticity [N/mm ²]	Density [t/mm ³]	CTE - linear α [1/°C]	Thermal-Conductivity -k- [t mm ² /S ³ °C]	Poissons Ratio [-]	Specific Heat Capacity [mm ² /S ² °C]
CrCN	3.1 10 ⁵	5.9 10 ⁻⁹	2.3 10 ⁻⁶	12	0.25	6.45 10 ⁸
G3500	1.50 10 ⁵	7.1 10 ⁻⁹	10.5 10 ⁻⁶	46	0.26	4.6 10 ⁸
Al7075	7.17 10 ⁴	2.81 10 ⁻⁹	25.2 10 ⁻⁶	130	0.33	9.6 10 ⁸
H13	2.15 10 ⁵	7.8 10 ⁻⁹	12.6 10 ⁻⁶	24.3	0.30	4.6 10 ⁸

H13 could be the pearlitic grey cast iron G3500 (automotive industry standard SAE J431) with a Brinell hardness of 207–255. From the coating point of view, there are some options for low friction partners.

In some investigations [6–10], advanced coatings (MoS₂ and DLC) come up to a very low friction coefficient of 0.05 or less. The limited thermal stability of conventional DLC can be increased with special coating technologies like silicon/oxygen and silicon/nitrogen (Si-O-DLC and Si-N-DLC) films [11]. In addition, other metal-modified hydrogenated amorphous carbon coatings, particularly tungsten-modified variants (a-C:H:W), and secondarily pure hydrogenated amorphous carbon coatings can be used as functional coating layer. As a result, the coefficient of friction in dry sliding against steel (100Cr6) can be varied in the range of 0.1 to 0.4; under full-lubrication with forming oil, the friction coefficient can be adjusted in the range of 0.05 to 0.11 [12]. At the end, the thermal stability is limited of about 500 °C. In comparison with other advanced coatings (TiN; TiB₂, Ti(B,N) [13] there are some options which are recently investigated within the ongoing project.

CrCN coatings have a similar friction coefficient at RT and about 400 °C. The hardness can be increased after an annealing. The friction coefficient and the wear rate can be reduced for a carbon content of about 10% at [14].

For the ongoing investigations, the following coating-substrate-systems compared with the sheet metal “workpiece” are taken in to the consideration (Table 1).

4. Theoretical investigations

To investigate the mechanical and thermal behaviour of coating-substrate-system there are some methods available, like analytically methods, Finite Difference Methods, Molecular Dynamics, Grid free methods and Finite Element Methods (FEM). Due to the common used application within the research community and also in the industry, the investigations where focused on the application and further development of the FEM.

4.1 Parallel computing approach

The influence of external loads on the stability of coating-substrate systems can be analysed by the finite element method. A parallel FEM-code, suitable for parallel computer systems with an arbitrary number of processors, was developed [8] and applied for different coating-substrate systems. The three-dimensional FEM discretisation of the coated forming tool can have some Mio unknowns. This way, deformations and stresses caused by external loads can be computed on a microscopic scale with sufficient accuracy and detail resolution.

A mechanism for data exchange and communication is needed when more than one processor of a distributed memory machine work together on the solution of a problem. That requires a physically existing network as well as additional software components for accessing this network (MPI, Message Passing Interface). For parallel FEM applications, the dominating programming model is Domain Decomposition (DD). For N processors, the simulation domain Ω (the forming tool’s geometrical model)

is divided into N non-overlapping subdomains Ω_i with boundaries $\partial\Omega_i$, and each processor does all the computational work related to “its” subdomain. All steps and data of the algorithm, from mesh generation, FEM assembly and solver up to the preparation of graphical post-processing may be performed and stored locally by processor P_i , with some local communication for data exchange over the coupling boundaries $\partial\Omega_i \cap \partial\Omega_j$ and some global communication for control purpose and *I/O*. The efficiency of the whole parallel algorithm is highly influenced by the quality of the DD: For a good load balancing, each Ω_i should contain nearly the same number of grid nodes, and the smaller the set $\cup(\partial\Omega_i \cap \partial\Omega_j)_{i \neq j}$, the smaller is the expense for the necessary data exchange. The most time and memory consuming part of the simulation program is the solver for the linear equation systems, even when sparse matrix techniques and fast solvers are used. Iterative methods should be preferred, because direct solvers show a bad error propagation and, due to the unavoidable fill-in, require too much storage when applied to large equation systems. Moreover, the FE matrices’ large condition- number, mainly caused by the inevitable high mesh graduation, requires special preconditioning techniques. The preconditioned conjugate gradient method (PCCG) is a well-established solver for FEM equation systems. Additional coarse-mesh preconditioning has shown to substantially reduce the necessary number of iterations. For the simulations of coated tools, a PCCG solver with hierarchical BPX preconditioning and an additional coarse-mesh solver was used. Based on this approach, coating-substrate investigations up to the microscopically level can be realised [8].

4.2 Modelling of coating-substrate-systems by AAFEM

The AAFEM contains many advanced features compared with other software tools. These features are:

- adaptive mesh refinement: based on this tool high accurate solutions with low calculation times and very successfully application for advanced coating-substrate-systems has been applied to new coatings.
- a special facility for so called super lattice coatings.

Partial Differential Equations to be approximated

The AAFEM is an FEM-Software [16], which can solve approximately the following partial differential equations (p.d.e.’s):

- (1) potential / reaction-diffusion problem (NDOF = 1)

$$-div(A(\vec{x})\nabla u) + \gamma(\vec{x})u = f(\vec{x}) \text{ in } \Omega$$

$$u = gD \text{ on } \Gamma D$$

$$\vec{n} \cdot A(\vec{x})\nabla u = gN \text{ on } \Gamma N$$
 with given $f(\vec{x})$, $A(\vec{x}) = diag(\alpha_1(\vec{x}), \alpha_2(\vec{x}))$ and $\gamma(\vec{x}) \geq 0$ (constant in sub domains of $\Omega \subset \mathbb{R}$).
- (2) Lamé – equation of linear elasticity (NDOF=2) with given $f(\vec{x})$, Young’s modulus $E(\vec{x})$ and Poisson’s ratio $\nu(\vec{x})$ (constant in sub domains of $\Omega \subset \mathbb{R}$).

In both cases Cartesian (x, y) -coordinates or cylindrical (r, z) – Coordinates are used. The Lamé-equation is given in its weak formulation only.

Boundary Conditions (b.c.’s)

We define $\partial\Omega = \Gamma_D \cup \Gamma_N$, with $\Gamma_D \cup \Gamma_N = \emptyset$.

The Dirichlet b.c.’s on Γ_D cut into two types. In both cases we define $u = g_D(x)$

1. In first case $g_D(x)$ can be a quadratic function prescribed by 3 values: $g_D(NA)$, $g_D(NE)$ and $g_D(NM)$; (N_A and N_E are endpoints of the edge E ; N_M is the midpoint of E)



Figure 4. Used mode.

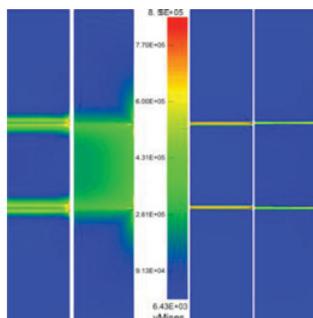


Figure 5. Influence of the thermo-physically coating properties on the Mises stress.

2. In second case $g_D(x)$ is a vector function. We can prescribe

- i. a “slip-condition”. That means that $\vec{u} \bullet \vec{n} = 0$ (normally to the edge-vector $\vec{E} : \vec{E} \bullet \vec{n} = 0$)
- ii. or a contact condition. $\vec{x} + \vec{u}(\vec{x})$ shall not penetrate an obstacle $[\vec{p} + \lambda \vec{r} : \lambda \in \mathbb{R}]$, with given \vec{p} and $\vec{r} \Rightarrow \vec{u} \bullet \vec{n} \geq (\vec{p} - \vec{x}) \bullet \vec{n}$. A software package has been developed to use this principle for the coating-substrate-simulation [16].

4.3 Selected results

One of the main issues for the HFQ[®] forming process is to remove the thermal energy from the sheet blank during the forming and tool quenching process step (TQ in Figure 1) in a very short time. In case of a standard sheet (Al7075; 270 mm × 925 mm; AT = 400 °C) is the total energy about 970 kJ. The thermo-physically properties of the applied coating should have an excellent heat conductivity and CTE combined with low friction. The used simplified model in Fig. 4 is a cut off from the complex 3D-forming Die-Coating-Sheet system as given in Fig. 2.

The influence of both has been investigated by extreme changed parameters. The used CrCN properties are given in Table 1. If the coating conditions are changed in to the combination (10xα: 0,1k – right and 0,1α:10k – left) the mechanical loading by v Mises stress is extreme concentrated in the coating area (right) or is relaxed (left) (Fig. 5). That’s indicates the responsibility of the job-coater to find out the best solution for α and k.

Furthermore, some investigations has been conducted on the use of low cost tool materials for the production of stamping tools to expand the size and range of components manufactured through HFQ[®]. The next Fig. 6 presents the results for a CrCN-Coating on common used H13 tool steel compared with G3550 cast iron.

For these investigations a axially-symmetrically model like Fig. 4 was used. As one result can be pointed out, that a combination of CrCN with G3500 reduce the thermal radial stress gradient of about 3 times in the coating.

5. Summary

Simulations are helpfully to find out the mechanical and thermal situation in coating-substrate-systems and can provide valuable indications for the job-coater to generate stable systems particularly for the ambitious HFQ[®] process.

* HFQ[®] is a registered trademark owned by Impression Technologies Ltd.

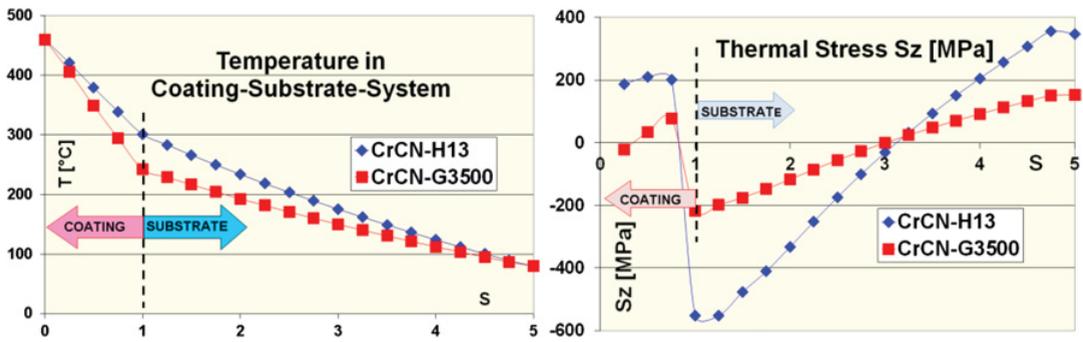


Figure 6. Temperature distribution and Thermal Stress S_z from the tool surface ($s=0$) up to the substrate.

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