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FEM Analysis of Clinching Tool Load in a Joint of Dual-Phase Steels

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The clinching tool with a die of 5 mm diameter with a specially formed gap and a punch of 3.6 mm diameter were used for mechanical joining of dual-phase steel sheets DP600 with the pressing force of 30 kN. The punch and die were deposited by PVD coating of CrN type with LARC technology. The coating state of each 50th manufactured join was evaluated by SEM. Cracks in the area of punch's radius were detected. The finite element method was applied for the assessment of punch load in the joining process.

Keywords: finite element method (FEM), clinching, CrN coating.

Introduction. The companies in automotive industry involved in developing and implementing new environmental solutions try to accommodate the requirements of legislation and customer demands including a better performance, luxury, safety and weight reduction [1]. Numerous materials and their combinations are used in car body production, such as conventional drawing grade steel sheets, high-strength steel sheets or aluminum alloys [2]. The use of high-strength steel sheets tends to increase to reduce the weight of automobiles. The mild steel panels are replaced with high-strength steel sheets [3]. Most of the utilized steel sheets are galvanized to improve car body life. The resistance spot welding is the most used joining method in car body production. However, the use of galvanized steel sheets causes considerable wear of welding electrodes due to the lower electrical resistance and melting temperature of the coating layer. Therefore, alternative joining techniques such as clinching have increasingly attracted manufacturers' attention [4–6]. Clinching is a simple and cheap mechanical joining process, by which two or even more sheets are deformed locally by creating a mechanical interlock without any additional elements such as bolts, screws, or rivets. In addition, clinching do requires no surface preparation such as drilling, cleaning, etc. Depending on the application and the required final mechanical strength, different clinching technologies may be used: with round or rectangular points, fixed or floating dies. The blanks are plastically deformed and the shape of the tools remains theoretically unchanged during the clinching process [7, 8]. The main geometry of forming tools includes: punch diameter, die diameter, depth of the die, radius of punch and die, angle of inclination of the punch and die. These dimensions influence the proper joint formation and the strength of joint [9].

The utilization of high-strength steels leads to higher requirements on the tool active parts and significantly enhances tool wear. For improving the mechanical and tribological properties, single or multi-layered PVD coatings with different mechanical strength or materials for the individual layers are used. Due to the requirements of industry for material coatings, the last few years have been a period of intensive development of PVD techniques. The basic properties of PVD coating include adhesion, hardness, thickness and roughness [10, 11]. CrN superlattice coatings have been widely used due to their improved mechanical properties, wear and corrosion resistance as compared to traditional monolithic coatings.

This research is focused on the evaluation of the tool wear for punch and die with CrN coating in the process of joining of hot-dip galvanized dual-phase DP600 steel sheets.

Simulation Procedure. Simulations of the round clinching joining process were carried out with utilization of the ANSYS workbench software. Because of symmetric character of joining process, clinching process can be modeled by the 2D axisymmetric simulation. Clinching die (∅5 mm) was considered an infinite rigid body, while both sheets and clinching punch (∅3.6 mm) were treated as deformable bodies. Clinching punch was modeled as a deformable body, in order to evaluate its load during mechanical joining of steel sheets. The simulation geometry including all parts is shown in Fig. 1.

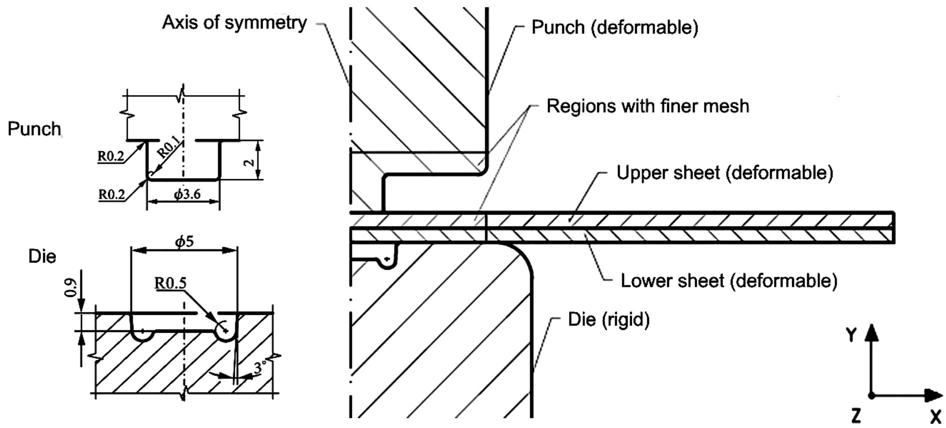


Fig. 1. Tool dimensions and the simulation model geometry.

A sheet holder was excluded from the simulation geometry by its replacement by the boundary condition, which will be described later. Only elastic properties were defined for the clinching punch including the Young modulus (210 GPa) and Poisson's ratio (0.3). These two parameters make possible to evaluate stresses and strains in the punch during joining of steel sheets. The same elastic properties were used for modeling of steel sheets with the yield strength of 377 MPa. A bilinear isotropic material model was applied, in order to describe the joint materials; behavior above the elastic range. The following boundary conditions were used during simulation: motion of clinching punch in Y axis driven by joining force of 30 kN (motion in X axis being restricted), fixed support at the bottom of the die, free motion in both directions for both sheets, rest of the sheets that should be covered by holder were restricted in Y axis and free in X axis. In order to properly describe holding of the sheets during joining, the sheet geometry was subdivided into two parts as seen in Fig. 1. To achieve reliable simulation results, mesh convergence analysis was performed. Sensitivity analysis showed that triangular element size should be 0.05 mm for all three deformable bodies. The same element size was used for a proper contact detection between the deformable bodies.

Figure 2 shows the mesh convergence analysis results and detail of meshed clinching punch. It can be seen from Fig. 2, that the critical zones are modeled with a finer mesh (0.05 mm). Large distortions of mesh during deformation of both sheets were eliminated by the adaptive remeshing based on the energy criterion.

Three contact zones are observed in the simulation geometry showed in Fig. 1. All three contacts were modeled as frictional with different values of the friction coefficient, being equal to 0.2 for the contact between tools and sheets, and to 0.4 for contact between

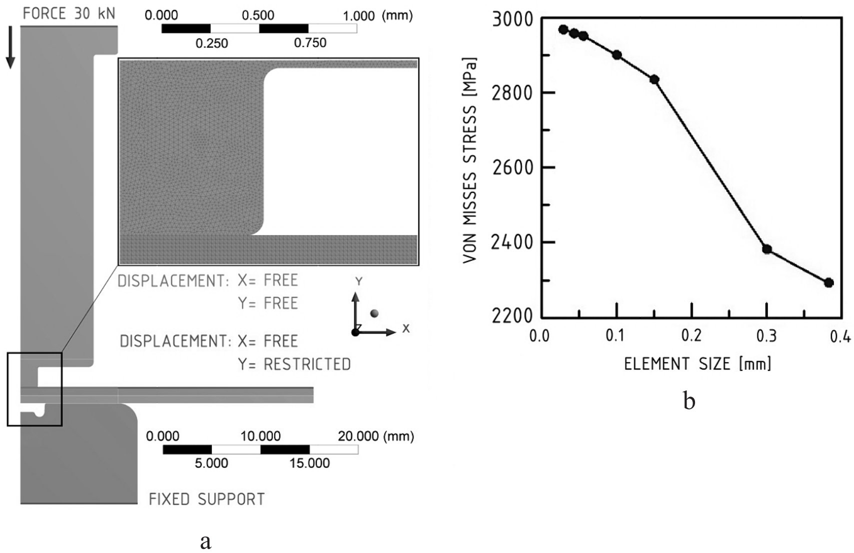


Fig. 2. Boundary conditions (a) and mesh sensitivity analysis (b).

joint sheets. Pure penalty contact formulation was utilized because of its ability to use the iterative solver to solve the stiffness matrix. The iterative solver based on the Newton–Raphson method is necessary for solving highly nonlinear problems as clinching joining method is associated with large deflections, contact and material response to load.

Experimental Procedure. The round clinching joining method with a rigid die was used to join steel sheets with a thickness of 0.8 mm. Dual-phase steel (DP600 grade) from the category of advanced high-strength steels was used in the experimental procedure. The basic mechanical properties of DP600 steel are shown in Table 1. The steel sheets were joined by the joining force of 30 kN, which was set to achieve joints with the appropriate load-bearing capacity.

T a b l e 1

Mechanical Properties of DP600 Steel

R_m, MPa	$R_{p0.2}$, MPa	A_{80}, %	n
600	330	20	0.14

T a b l e 2

Basic Characteristics of CrN Coating

t_f, μm	E, GPa	H_{IT}, GPa	S_a, μm
2.11	380	31	0.51

Both tools (clinching punch and die) were coated with the PVD-CrN coating by the LARC deposition method, manufactured from tool steel for cold-working applications (grade 1.2990). Various tests were conducted to measure the basic properties of coating; results of which are shown in Table 2. The coating state at the initial phase and during joining cycles was monitored by the scanning electron microscopy (SEM), in order to detect any defects that could deteriorate the tool operation or residual life. Potentially critical zones of clinching punch and die surfaces were identified for the SEM monitoring.

In total, the following numbers of coating monitoring zones were set: five for the die and three for the punch. Both tools were scanned in the normal direction to the symmetry axis shown in Fig. 1 with a scanning period (cycle) being set to 50 manufactured joints.

It was concluded from previous experiments, that the die coating exhibits no degradation or failure of any types or mechanisms during quite a long initial period of the joining cycles. Considering the fact that clinching die wear is not as intense as that of the punch, only the latter was monitored for different joining cycles. Figure 3 shows the punch critical zones with their respective designation. Line *1* in Fig. 3 defines the unified direction for acquiring the SEM images after each joining cycle. The following designations were used for the critical zones covered by the SEM monitoring: *P* is punch protuberance*, PR* is radius around the punch protuberance, and *PV* is the punch protuberance vicinity.

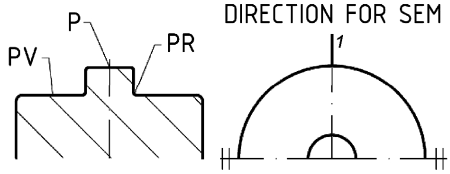


Fig. 3. Designation of the punch critical areas for SEM imaging.

The basic view of the clinching punch scanned at ×31 magnitude, as well as all three critical areas of the clinching punch scanned by SEM at ×1000 magnification are depicted in Fig. 4 with the same designations as Fig. 3. These images reveal the CrN coating for the initial state of the punch, at which no joints were produced yet. At this stage the coating exhibits no discontinuities that could deteriorate its operation. A specific texture in the form of tracks was observed at larger magnifications.

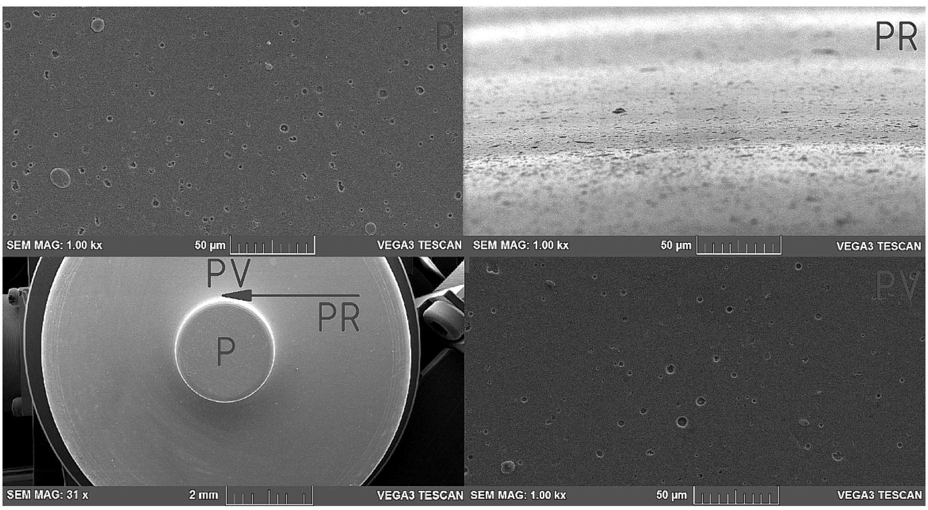


Fig. 4. Clinching punch with the initial state of the CrN coating (×1000).

The CrN coating of this tool in the *P* and *PV* zones was found to be covered with spheroidal macroparticles, which dimensions differed from 1 to 10 μm (Fig. 4). Moreover, the surface pitting was observed, whose density was larger than that of macroparticles The latter particles are known to appear as a side effect after application of the LARC deposition method and are considered as its drawback due to the increased roughness of the coating surface.

Results and Discussion. In total, 200 joints were manufactured by joining of the advanced high-strength DP600 steel. The clinching punch was scanned by SEM every 50 manufactured joints for evaluation of the coating state during the joining period, in order to reveal any sign of tool or coating damage in the critical zones depicted in Fig. 3. The FEM simulation was used to assess stresses and strains in the punch during joining of two steel sheets. Moreover, the FEM simulation made it possible to identify the most loaded part of the punch in the joining process. Figure 5 shows the CrN coating in all critical zones of punch after 200 manufactured clinching joints. The same magnification (×1000) was used as for imaging of the CrN coating initial state.

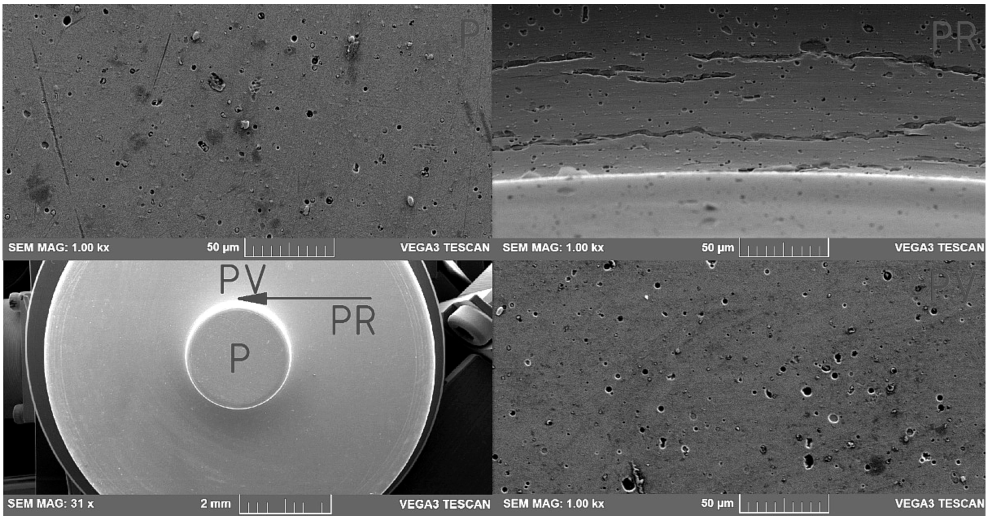
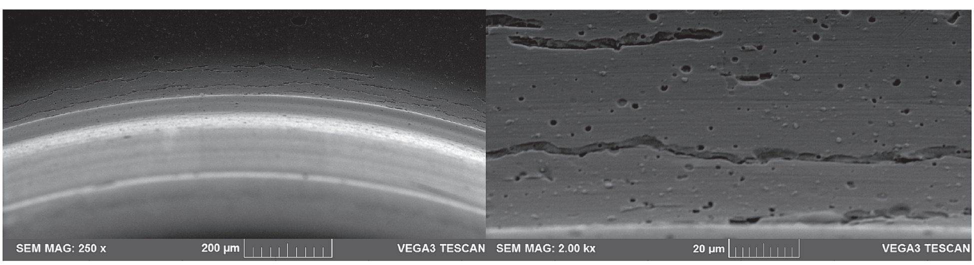


Fig. 5. Clinching punch – CrN coating state after 200 joining cycles (×1000).

The comparative analysis of the initial state and that after 200 manufactured clinching joints indicates the process of macroparticles' density reduction at the coating surface. This reduction is the most pronounced in zones of direct contact between the punch and upper sheet surfaces (Fig. 5, *PV* and *P* zones). Pressing of the upper sheet by the punch during the clinching process causes friction. As a consequence, spheroidal particles are removed from the coatings surface, which phenomenon should be notable by comparing the field parameters. Very fine scratches are visible at higher magnification of SEM imaging (×2000). Cracks in coating were observed in the critical zone *PV* (Fig. 5). The area around punch's protuberance was surrounded with transverse cracks, which are visible even at lower magnification (×250), as is shown in Fig. 6.



a b

Fig. 6. Cracks in CrN coating at punch's protuberance radius critical area (*PR*).

In addition, the FEM simulation results show the stress-strain evolution in the punch with it progresses towards the die cavity to form a joint. Figure 7 illustrates evolution of the equivalent von Misses stresses in punch during the elemental stages of clinching joint forming: drawing, compression, upsetting and clinching. The finite element mesh was removed from pictures to maintain good visibility of the simulated results.

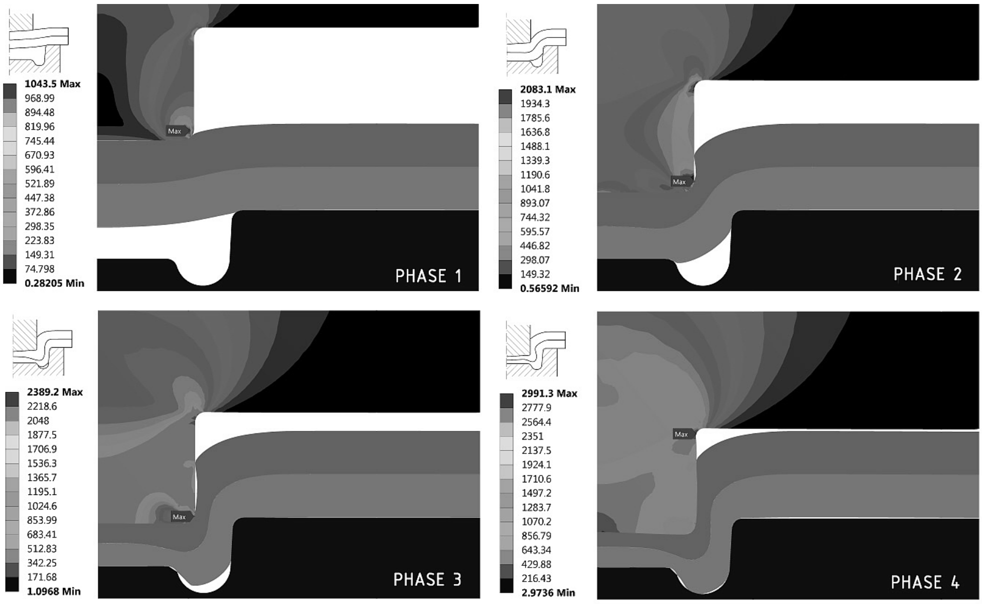


Fig. 7. Equivalent von Misses stress (in MPa) progression in punch during clinching joining.

The finite element simulation shows that the radius around the punch protuberance is the most loaded part of the clinching punch. The equivalent von Misses stress slowly increases with each stage of of the joint forming. The highest value of stress (2991.3 MPa) was measured in the critical zone *PR*. There can be seen a coherence between the SEM images and the FEM results: cracks in the CrN coating appeared in the most highly-loaded zone, as follows from FEM results. Tensile or Hertzian cracks progressing to chipping or spalling of coating can occur when a low-hardness substrate is combined with a high-hardness coating. This phenomenon is related to deformation of the substrate, which occurs when a certain material parameter is exceeded. Moreover, surface microcracks are usually generated in the discontinuities of the surface topography such as grinding marks. Such machining marks around the punch protuberance are clearly visible in Fig. 6a. In this case, microcracks initiate and propagate parallel to the surface at a few micrometers' depth along the machining direction, which may lead to formation of microspalls.

Conclusions. Evaluation of tool wear during clinching/joining process of two steel sheets was performed when joining the advanced high-strength steel sheets. In total, 200 joints were manufactured using a clinching punch and die with the CrN coating. The coating state was evaluated and monitored by the SEM imaging after each 50 manufactured joints. Based on the results of previous experiments, wear of the clinching die is less pronounced as compared to the punch. Hence, the focus was set to load and wear of the punch during joining of dual-phase steel sheets (DP600). Cracks in the punch radius vicinity (surrounding the punch protuberance) were detected by SEM when imaging with a low magnification (×250). All other critical zones exhibited only a minor wear in the form of removed spheroidal particles, which were produced during the CrN coating deposition.

These macroparticles were removed by the sliding contact between the surfaces of coatings and steel sheets. This phenomenon can be of advantage, because macroparticles tend to increase the surface roughness of coating. The finite element analysis of joining process that the PR zone has the highest stress level. When some discontinuities in the form of grinding or machining marks are observed, the stress level can increase and microcracks tend to initiate and propagate along the machining direction, as shown in detailed SEM images.

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