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Influence of material damage during the forming process on the vibration fatigue behaviour of a clinched connection.

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Abstract. This paper presents the results of an analysation of forming damage during the joining process on the fatigue failure behaviour of a clinched connection. The two joining partners out of aluminium, AlMg0.7Si on the punch side and AlMg3 on the die side, are clinched with a flat clinching system and the use of a preformed hole at the die side. By the use of two different geometry variants it could be shown, in fatigue Wöhler tests, that the fatigue failure behaviour is influenced by the material damage in the deformed material of the clinch. The material damage during the clinching process could be calculated with the help of FE-Simulations. So it was possible to show that more forming damage during the joining process causes less lifetime of the connection.
Keywords: Joining, Damage, Fatigue

1 Introduction

The mechanical joining process clinching is getting more and more important for the automotive industry. Especially for light weight designs, clinching is a very interesting joining method to connect sheet metal components. The main advantages of clinching are that there is no need of additional joining parts like screws, there is no heat injection in the joining partners, there is no emission of welding gases during the clinching process and there are no problems with coated surfaces of the joining partners. [1, 2]

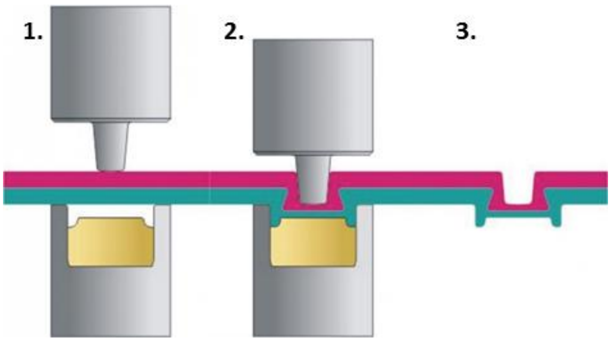

Fig. 1. Sequences of a no-cutting, single part die clinching process [3].

During the clinching process, the material of the joining partners is deformed by a punch and a die to get an interlocking connection. The joining process is illustrated in picture 1. The die is placed under the bottom metal sheet, the punch is placed above the upper metal sheet. When the punch moves downwards it presses the material into the die. Because of the geometry of punch and die the material is deformed in a way that an interlocked connection is formed. During this process the material is highly deformed and this deformation could possibly affect the material properties. During the forming process the accumulated plastic strain of the material reaches 400%. This is only possible with ductile metals and under pressure dominated load. [1, 2, 4]

In this work a special clinching variant was analysed which will later be used to connect the housing parts of an electronic control unit (ECU). The main reasons why clinching was chosen as a joining method for the product were, the low costs per part, that it is possible to join partners with coated surfaces and that no finishing of the connection area is necessary.

1.1 Special Clinch Method

In this work, a special clinching variant was examined. Due to the lack of space, it was not possible to use a standard clinching method with a single or a multiple part die to connect the two parts of the ECU housing. The available space was sufficient only to place in a nearly flat anvil. The used clinching method is shown in picture 2. The bottom metal sheet was provided with a preformed hole including a chamfer at the lower side of the hole. Instead of a die, a nearly flat anvil was used. During the clinching process, material of the upper metal sheet is formed through the hole and behind the chamfer. So it is possible to build up an interlocking connection.

1.2 Fatigue Loads

Automotive components are subjected to high vibration loads. Consequently, it is very important to have a closer look at the fatigue failure behaviour of the connection under these high vibration loads. It is necessary that these vibration loads cause no failure of the clinch during the lifetime of the vehicle. The main focus of this work lies in understanding how the change in material properties during clinching influences fatigue failure behaviour. The question is, to what extent changes in the material properties can be allowed to ensure that there will be no fatigue failure of the connection over lifetime.

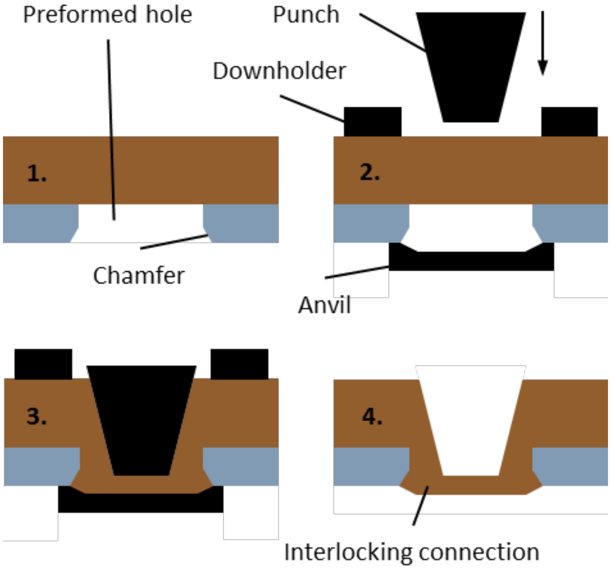

Fig. 2. Special clinch geometry used for electronic control unit housing.

2 Research method

To reach the goal there were different research methods used. The mainly used method was the Finite Element Method (FEM) to calculate the changes in the material properties during the forming process. With this method it is possible to have a look inside of the material during the clinching process. It is possible to predict the effects of cold hardening and also to calculate the damage during the forming process. To use FEM to calculate the hardening effects, it is necessary to have the hardening curves of the used material which have to be measured in experiments. The material hardening can be analysed with the help of micro Vickers hardening tests on cross sections, these cross sections will also enable validation of the forming simulations.

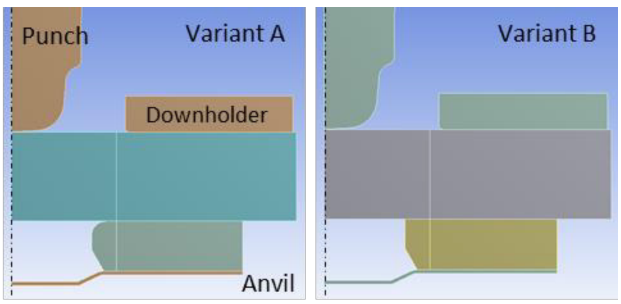

Fig. 3. Geometric difference between the two analysed samples variant A and variant B.

The fatigue failure behaviour can be analysed with fatigue Wöhler tests. To show the influence of the material damage during the clinching process two different geometries of the preformed hole were compared. Picture 3 shows the geometric difference between the two samples. On the left side variant A is printed with a rounded edge on the upper side of the bottom metal sheet. The right side shows variant B with a sharp edge on the upper side of the preformed hole.

2.1 Material and Data

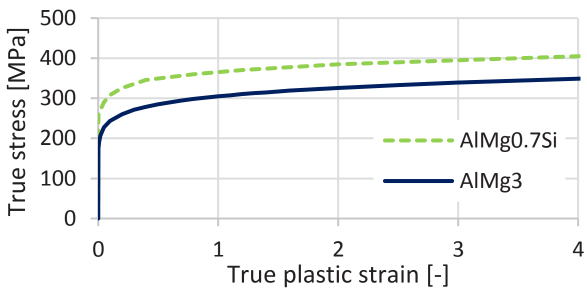

Fig. 4. Hardening curves used for the forming simulations.

The used material in this work was aluminium. More specifically, AlMg3 for the bottom metal sheet with the preformed hole and AlMg0.7Si for the upper metal sheet with the high deformations during the forming process. To simulate the forming process it is necessary to have hardening curves of the used material until high deformations. These hardening curves cannot only be calculated out of tensile stress test, because with tensile stress tests the specimens fail at a deformations value of 10-15%. But for the simulations the hardening curves are needed until a deforming value of 400%. Because of this a test program was done to measure the hardening behaviour until an accumulated plastic strain of 200%. In this test program tensile tests have been done of different metal sheets. The metal sheets have been preformed in a rolling process to get specimens with a different value of accumulated plastic strain. So it is possible to measure the stress strain curves for different values of accumulated plastic strain and put them finally together to one curve. Out of this stress and strain curve hardening cure can be calculated. The sector between 200% and 400% strain has been calculated with an exponential law. In picture 4 the used hardening curves are shown.

2.2 Forming simulation

To simulate the forming process, the FE-Program Ansys was used. With Ansys mechanical it is possible to simulate the forming process in an axis-symmetric 2D-Model. The remeshing tool of Ansys (since Ansys 17.0) allows to simulate forming processes with high deformations in the implicit Ansys code. With this method it is possible to get the results of the simulation very fast. The model was build up with the hardening curves shown before for the two different aluminium metal sheets. The tools (steel) were modelled as a linear elastic material model with an E-module of 210 GPa. The friction between the parts was modelled with the coulomb law of friction. Between the two aluminium metals a friction factor of μ=0.2 was set. Between the aluminium metals sheets and the tools, the friction factor was set to μ=0.15, except between the punch and the aluminium metal sheet. This friction factor was set to μ=0.1 because the punch is oiled in the clinch process.

2.3 Damage Model

To calculate the damage in the material while the forming process the Oyane criterion (1) was used. Behrens et al. have shown that this damage model works for clinching processes [5].

$$C = \int_0^{\bar{\varepsilon}_{pl}} \left(\frac{\sigma_m}{\bar{\sigma}} + B\right) d\bar{\varepsilon}_{pl} \geq C_{crit} \qquad (1)$$

The Oyane criterion uses stress triaxiality $\frac{\sigma_m}{\bar{\sigma}}$, equivalent plastic strain $\bar{\varepsilon}_{pl}$ and two material parameters B and C_{crit} to calculate the damage during the forming process. The two material parameters have to be defined. Behrens used 2.36 for the parameter B out of the work from Chen [6] and set C_{crit} to 2.13 for his studies [5].
In his studies he used an aluminium material similar to the material which is used in this work.

2.4 Micro structure analyse

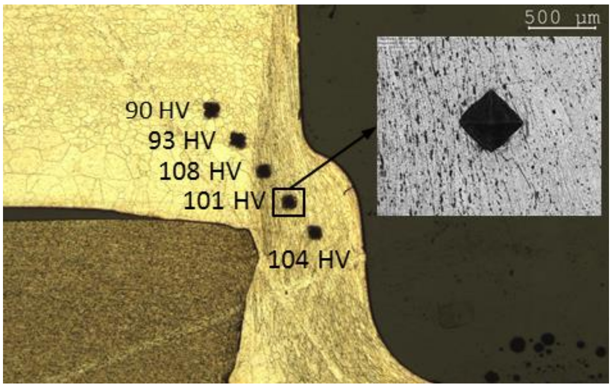

Fig. 5. Micro Vickers hardness test of deformed material after clinching process (exemplified by variant B).

To analyse the micro structure of the clinch and to validate the simulated results clinch specimens were built up. With the help of cross sections it was possible to observe the microstructure inside the clinch. A micro Vickers hardness test was done to show the effects of cold hardening during the forming process. The micro hardness measurement was carried out according to DIN EN ISO 6507-1. The impressions were generated with a load of 10 kg. The micro Vickers hardening test on a cross section is shown in figure 5 exemplified by variant B. Unfortunately, the method is not exact enough to represent differences between variants A and B. Picture 5 also shows the microstructure of the clinch. It is shown which area of the two joining partners is deformed and how strong. The form of the grains changes form nearly square to rectangular grains which could be 5 times longer than it is wide. The comparison between the micro Vickers hardening measurement and the deformed grains shows that the hardening increases with more deformations in microstructure. So it is possible to evaluate the hardening effects on the deformations in microstructure.

2.5 Fatigue Damage Failure

To analyse the fatigue behaviour of the clinched connection Wöhler fatigue tests have been done. In this study the main attention was on the fatigue behaviour under peeling tensile load of the clinched connection.

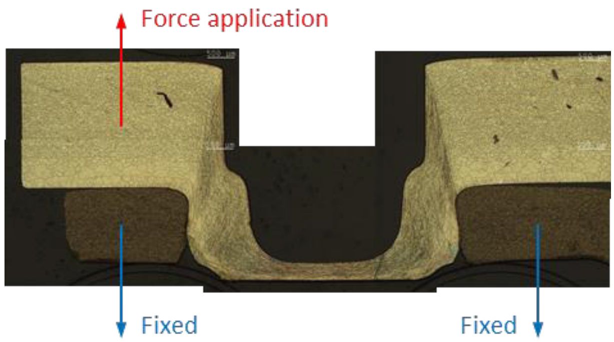

Fig. 6. Force injection of the peeling tensile loaded fatigue Wöhler tests (exemplified by variant A).

Therefore, specimens of clinched connections of variant A and B have been tested under peeling tensile swelling load as shown in picture 6. In the Wöhler test the bottom metal sheet is fixed. The upper metal sheet is loaded on one side with the tensile force. As a result, the clinch is under a peeling tensile load.

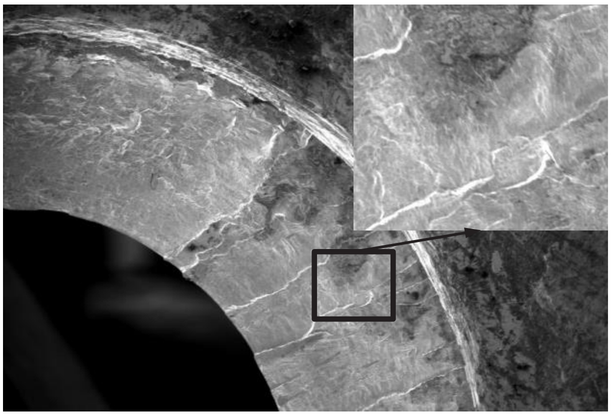

Fig. 7. SEM picture of fatigue crack fracture surface of the clinch (exemplified by variant A).

After the Wöhler tests, the fracture surfaces were analysed under a scanning electron microscope (SEM) which clearly shows that the fracture is a fatigue crack and not a static crack. Figure 7 shows a typical image of a fatigue crack, with fatigue striations. The picture shows that the whole fracture surface failed under fatigue.

3 Results and Discussion

The results of this work start with the results from the fatigue Wöhler experiments. Subsequently, the results of the FE-Simulations are presented.

3.1 Fatigue failure behaviour

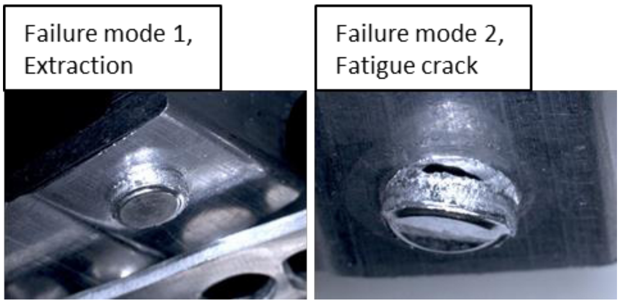

Fig. 8. Failure modes of fatigue tests, extraction on the left and fatigue crack on the right side (exemplified by variant A).

The fatigue Wöhler test has shown two different failure modes for the clinched connection. The first failure mode is the extraction of the upper metal sheet form the bottom metal sheet. This failure is shown on the left side of figure 8. The second failure mode is a fatigue crack through the deformed material of the upper metal sheet, shown on the right side of figure 8. The occurring failure mode depends on the testing force. For higher forces the clinch failed under mode 1 and for lower forces the clinch failed under mode 2. In the used product only the lower force is expected. So that failure mode 2 is the interesting one.

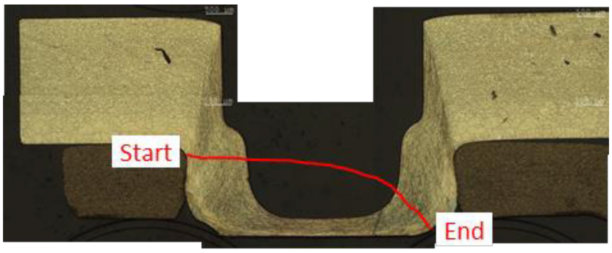

Fig. 9. Fatigue failure crack path of failure mode 2 (exemplified by variant A).

The path of the fatigue crack of failure mode 2 was similar in every clinch specimen, as shown in Figure 9. The picture shows where the fatigue crack starts and where it ends. Important for the clinch as connection is the area where the fatigue crack initiates. The Wöhler test has been done for both geometry variants A and B. The compression between the two variants shows that the specimens of variant B failed earlier than the specimens of variant A. Variant B has nearly 50% less lifetime versus variant A. A possible reason is that because of the sharp edge of variant B it is a more cutting forming process than in variant A. Even though there are no forming process cracks it is likely that the sharp edge causes a higher forming process damage in the area were the fatigue crack initiates. So that the fatigue crack can initiate earlier or grow faster in the area with higher forming damage. This gives the idea that the loss of lifetime might depend on a higher predamage of the connection during the forming process. If it is possible to calculate the predamage during the forming process and correlate it to a loss of lifetime, it would be possible to predict the lifetime of the clinch only based on the forming simulation. This would help to improve the punch and anvil geometry keeping the fatigue behaviour in mind. But for this first a working forming simulation model is needed.

3.2 Comparison between simulation and experiment

To ensure that the simulation model gives the right results it has been compared with the experiments. Figure 10 shows the experimentally measured and simulated force displacement curves of the clinching process. In the figure it can be seen that the simulation model is able to calculate the force displacement curve to a very good degree of accuracy. The difference between the two curves can be explained by the fact that the forming process is simulated in a 2D-Model and the real process is not completely axial-symmetric.

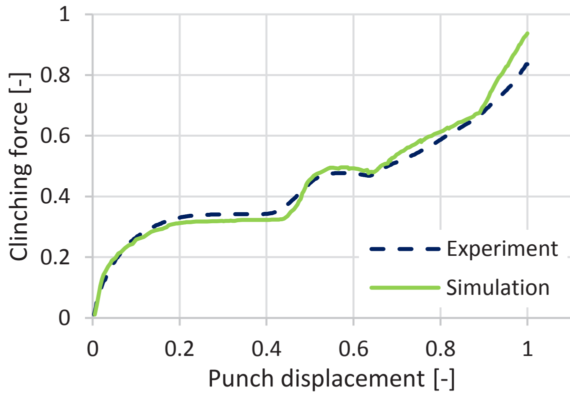

Fig. 10. Force displacement curves of the clinching process in experiment and simulation (exemplified by variant A)

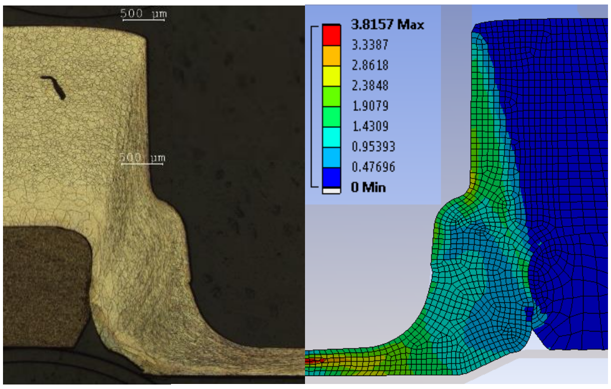

Fig. 11. Compression of the simulated geometry and a cross section of the clinch (exemplified by variant A).

Figure 11 compares the geometry of the clinch. On the left side the cross section of the real clinch is shown while on the right side the simulated geometry is shown. The colours show the value of equivalent plastic strain of the different area. The compression shows that the simulation model is able to describe the forming process. The left side of the figure also shows the deformation of the grains after the forming process. The higher deformed grains indicate a higher degree of hardening. The simulation model is also able to calculate this effect. The areas with the highly deformed microstructure in the real clinch match with the areas with high plastic strain in the simulation. The used simulation model is able to calculate the right force displacement curve of the forming process

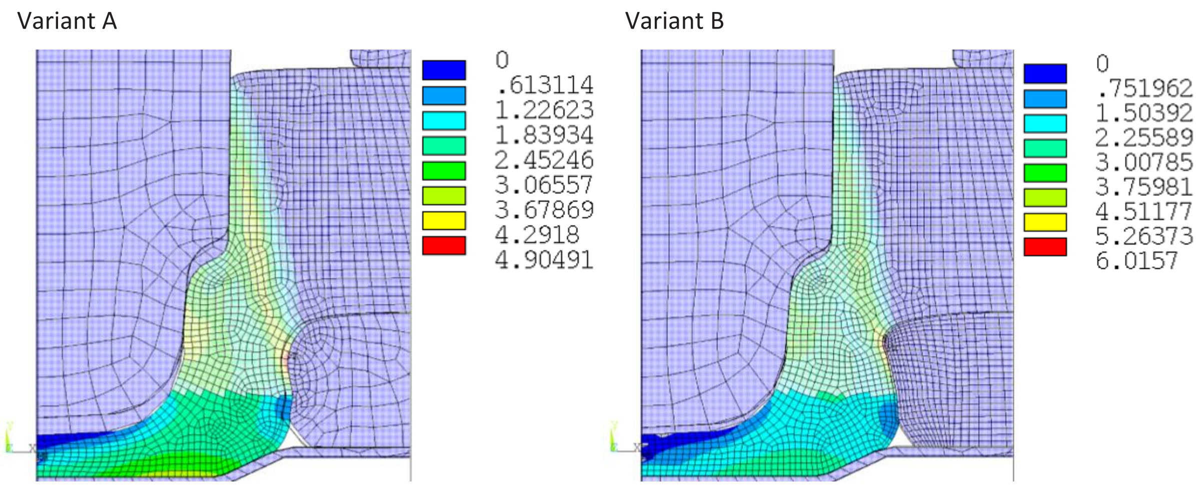

Fig. 12. Simulated damage values after the clinch process for variant A (left) and variant B (right).

and also the right material flow during the forming process including the effects of cold hardening. Now it has to be analysed if it is also possible to calculate a fitting damage value including the presented damage law.

3.3 Calculation of the damage value

In chapter 3.1 we presented that clinches of variant B fail more quickly than the clinches of variant A. A possible reason for this effect is that because of the sharp edge, the material in the area where the fatigue crack starts is more damaged during the clinching process. So the fatigue crack process starts earlier or grows faster. To demonstrate this effect, the forming process of two variants are simulated and the damage was calculated with the help of the Oyane damage model. Figure 12 shows the calculated damage values for the two variants A and B. The figure shows that the damage value of variant B (6.0) is higher than the damage value of variant A (4.9). This fits to the idea that the process forming damage of variant B is higher than in variant A. But both damage values exceeded the value of C_{crit} from Behrens. This would mean that with the used damage model including the used parameters both variants should have process forming cracks. As the cross sections shows no cracks in the areas with the high damage values, the damage model or the parameters from Behrens cannot be used to calculate cracks occurring during the forming process in this use case. Because of this other parameters for the value of B were tested, like B=1 or B=0.3. For all tested parameters of B the value of C_{crit} was higher for variant B than for variant A. But without tests where the value of C_{crit} is really reached it is not possible to adjust the parameter setup of the damage model for the used material.

4 Conclusion

This paper has shown that the vibration fatigue failure behaviour of a clinch connection can be influenced by damage effects during the clinching process. It could also be shown that more forming damage leads to an earlier failure in the fatigue Wöhler tests. The work also shows that with FE-simulations it is possible to calculate the forming process including effects of hardening. It was possible to simulate the right force displacement curve of the clinch process and the resulting geometry. This shows that the simulation model used works properly and is able to simulate the process sequence of clinching in a realistic way. A higher damage value corresponding to Oyane law is an indication towards the reason for an earlier fatigue failure of variant B. It was not possible to use the value of C_{crit} from literature (Behrens) to calculate forming cracks. Here the used parameter setup needs correction. As a result of such a correction, it could be possible to calculate the critical damage value encountered during the forming process leading to forming process cracks.

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