UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

EXPERIMENTAL AND NUMERICAL EXAMINATION OF CLINCHED JOINTS

Booklet of PhD Theses

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1. INTRODUCTION

In my dissertation I am dealing with the field of clinch joining. The last couple of years the research and industrial usage of clinch joints is started to increase, however the first patent of the technology is more than 100 years old. The development of the clinching technology has several aspects.

On the one hand the clinching is a joining-element-free technology, thereby the total mass of the products could be smaller, compared to other methods (e.g.: bolts or riveting). Thus, the main user of the joints is the automotive industry, besides to the household and computer industry, because of the more and more strict environmental protection rules and laws in the EU and worldwide, as well. On the other hand, during clinching no harmful gases are produced which is a huge befit compared to the spotwelding technology. Further important property is that the process can be able to automize or robotize, due to the great repeatability of the joints during mass production with small or negligible errors, and it is a quite fast procedure.

The standardization is an especially important need in the industrial usage, but previously the clinching has had limited standardized procedures, that was the driving force of the academic research.

The academic research has started to react to the needs of the industry in the field of clinch joining. However, the promising results of the research had been used by the industry as a daily routine. The industrial usage and academic research are related to each other. In the past 20 years the research is increased because of the computing performance has increased, and by this the numerical solutions are getting better and better, so the finite element models could be more complex and more detailed, which drives to better results, and could be possible to determine results without expensive testing.

The material science, as a part of the dissertation, is closely related to the modelling, since for the numerical description of the material behaviour we have to know the applied materials. The mathematical description of material laws, frictional conditions, failure modes is getting more complex and more precise, and these advanced models are getting involved for the daily routine through different software packages. Some mathematical models are capable to handle the property deviations from standard values of materials and geometrical inaccuracies of the tools, so the process optimization procedure is increased, for instance the robust design methodology. Due to this development of different software and information technology the development of clinching tools is getting faster, and new variants have been developed, which could not be possible without these new technologies.

Even so the material testing has also an important role in the development, because without the knowledge of the right material parameters it is impossible to determine the needed laws and applied models.

However, the simultaneous usage of the two fields, experiment and modelling, can reduce the or eliminate the classical design methodology the so-called trial-and-error, because the cost of the experiments will less, and also the manpower, and several geometrical and loading cases could be enough to assess by numerical methods, so the decision-making process could be easier.

1.1. Goals of the dissertation

In my dissertation I have presented the different variants of the clinching process. I would like to use my results in the industry. My goal is to present results which could be useful in simulation engineering roles, design phases next to the mass production.

I have started my research with the overview of clinch joining related literature. I have briefly reviewed the place of the clinching among the relative technologies, and its relation to them. I have dealing deeper with the applied type of clinch joining variant. I have presented the pros and cons of the technology and summarize the questions of the quality assurance. The biggest advantage of the clinch joints compares to the relative technologies, that dissimilar materials could be relatively easy to join, so I have had research on the joining of clinching of dissimilar materials. During the presentation of different clinching variants according to the literature, I would like to show that the clinching technology is a remarkably diverse, complex, and complicated technology.

The dissertation has two main parts, on the one hand the experimental work that I have done and their results and conclusions, and on the other hand the results and assessment of the finite element modelling. The two parts are close to each other, so where its possible the methods discussed parallel.

In the modelling part I have examined the affecting parameters of the joint made by DP steels, like friction or tool geometry.

The aim of the dissertation is to analyse the technology from different point of views, to develop a method which can helps to determine tooling geometry for aluminium alloy based on the original tools. The goal is to reach the highest possible strength with the new geometry.

Furthermore, based on the literature, the tensile strength of the homogeneous joints could be estimate based on analytical solution, so I decided to develop a method which can supplement the analytical method with an extra term which can handle the order of the dissimilar materials.

In the literature the dynamic tests of the clinch joints are dealing with the fatigue and the high-speed tensile test. In my dissertation the impact testing of joints was used as dynamic testing method. Previously no one was decided to perform this type of testing for clinching joints according to the literature review. According to the results of the experiments, it can estimate the reliability of the joints and furthermore, the direction of the impact is affecting the value of absorbed energy, in other words the joint is orientation dependent from the point of view of impact loads.

In a chapter I am dealing with the equivalent or simplified modelling techniques because these descriptions of the clinched joints can be useful for industrial simulation of multiple joints at the same time. In this case the focus is on the strength of the joint instead of the determination of the joint geometry or the joining process parameters. This role is important and have benefits from the point of view of machine design.

2. LITERATURE REVIEW

The technology is quite old, first patent of clinching is dated to 1897 **Hiba! A hivatkozási forrás nem található.**. The start of the industrial usage of the clinching technology is dated to the end of the 1980's. The main reason of the quite slow development is the truly complex nature of the technology. The complexity comes from the lack of experimental data, which drives to several uncertainties. In complex structures small inaccuracies could be dangerous in so many levels. The modification of the tool geometry causes quite high changes in the strength of the joints, the experimental examination of these changes could be extremely expensive. Nowadays, the research is highly intensive in relation to the clinching technology [3][4][5], however these days the numerical examination is often forgo to the experiments, because it is faster, cheaper and, which is important, a preliminary result can be achieved for a new geometry variant. A simple way of examination of the joints is possible with the usage of finite element method. It could be a little controversial, to have good model must have to perform material tests also, but the usage of the simulations can reduce the trial-and-error phase in the development [8].

The academic research started with the PhD dissertation of J. P. Varis [2]. Since then and especially in the last couple of years several PhD was deal with the clinching from different point of views [8][6][7], this fact indicates that the clinching joints are important industrial application. The most valuable dissertation is the work of Coppieters [8]. Interesting study from the point of view of material testing, and his numerical results provides a great basis for the further development of the analytical methods. The book of Balawender [9], related to the clinching, is a milestone. The Hungarian research is based on the work of Tisza et al [10][11].

The clinching is mostly used to join thin sheets, but some publication is deal with special cases, like clinching of thick sheets [12]. The peak value of the measured forming force is reached 800 kN, and the total clinched thickness was 12 mm.

The compare to the relative technologies (spot weld, bonding, rivets), the basic clinch joints have the advantages as the lack of supplementary joining elements or the disuse of heating. During clinching, due to the geometry of the tools, local plastic deformations occur, and the result of the process is the joint. The tools could seem to be simple, but their special geometry and in some special cases their relative motion is overly complex. Fig. 1. shows the process of the so-called basic type of clinching, the spot clinching. During the process the punching tool is pushed into the die, after the joint formation the tools are removed, and because of the residual, plastic deformations, the joint is getting ready.

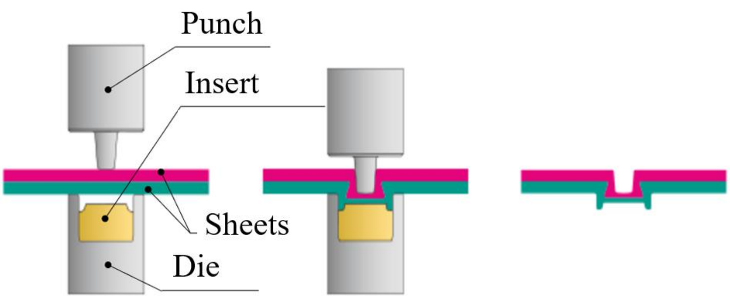

Fig. 1. Clinching process [13]

During the process due to the specially manufactured tools, the sheet, closer to the punch (upper sheet) is flow into the die sided sheet (lower sheet) the special joint geometry is made. The result of this process is the main, form locking mechanism, furthermore the friction between the sheets provides force locking also. Some special cases (e.g., hybrid joints) the material locking is realized by adhesive materials in between the sheets, which can highly increase the load bearing capacity of the joint.

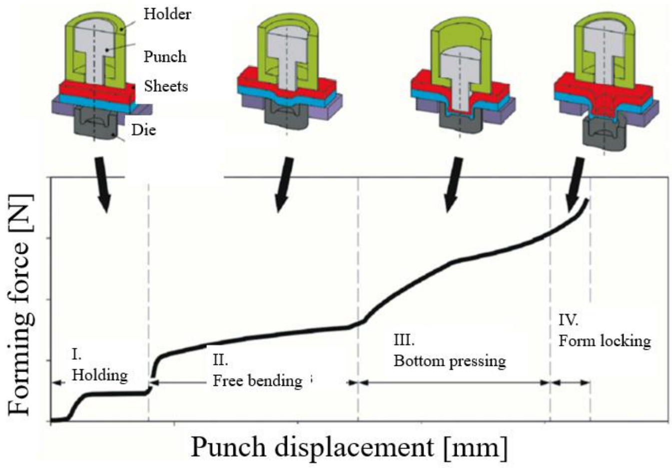

Fig. 2. Characteristic process force-displacement curve [14]

On the Fig. 2. it can be seen the characteristic curve of the process with depicted moments of the forming. The first stage is the application of the holder force to prevent the movement of the sheets. In the dissertation this stage has been neglected because of the negligible force values compare to the maximal forming force (a couple hundreds of Newtons). The second stage is a deep drawing like mechanism, firstly a free bending part until the stress reaches the flow stress. This mechanism can imagine as the classic deep drawing process, but the stress-strain state is much more complex in both sheets. In the first part of the second stage the strains are elastic, then they reach the flow stress, and the plastic forming started. The third stage of the joint forming is starts when the lower sheet is touching the bottom of the die. In this stage the sheets are pressed to the bottom of the die, and because of the design of the die, the sheets start to flow radially into the die's groove. Because the flow is inhibited by the geometry, the upper sheet is starts to flow into the lower sheet. The diagram does not show the fifth stage, when the tools are removed from the joint. On the diagram it would be a linear line with a small bump.

On the characteristic curve it can be see the typical parts of the process, like the lower sheets reached the bottom of the die. From the lock forming point of view the fourth stage is the most responsible. The displacement is small, but the force increments getting higher because of the hardening of the material and the inhibited flow.

During my research I have used the Department's TOX tool for the manufacturing of spot clinch joints. The tool can be seen in Fig. 3., the C-frame has been installed into the MTS 250 electro-hydraulic universal material testing machine. A horizontal plate has been installed to the C-frame, the plate is a supplementary element to prevent the specimens in their movement and provides their proper position. The schematic drawing of the tool can be seen on Fig. 4.

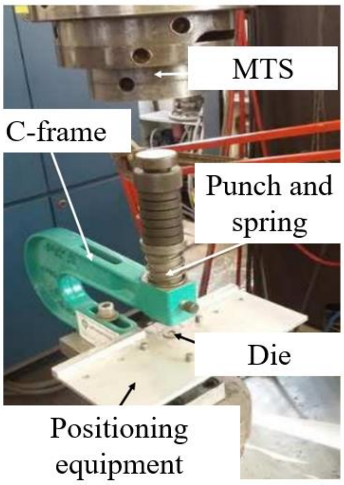

Fig. 3. TOX clinching tool

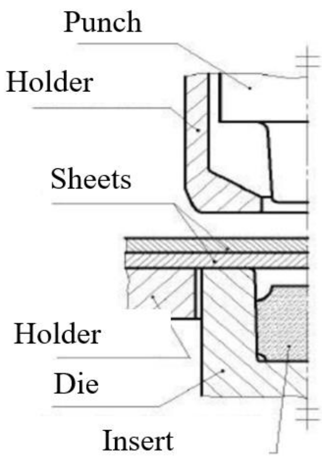

Fig. 4. Schematic respresantation of the tool [11]

The schematic representation of a spot clinch joint with its most important geometrical characteristic values can be seen in Fig. 5. According to the literature the three main parameters, t_N – neck thickness, C – undercut, t_B – bottom thickness, were taken into consideration.

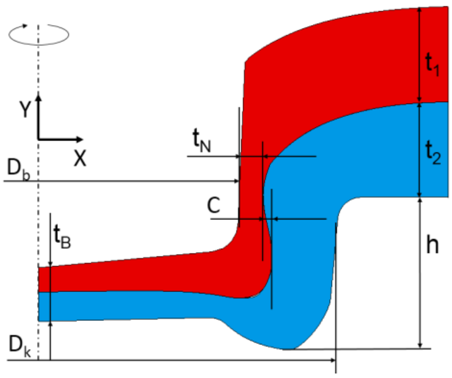

Fig. 5. Schematic cross section of spot clinched joint and main geometrical parameters

3. RESEARCH METHODS

During the literature overview I have getting familiar with the testing and modelling methods of the clinching technology. After that I have performed the needed material tests and experiments. The related experiments and measurements were performed at the Laboratory of the Institute (ME-ATI) at the University of Miskolc. The determination of the structural and chemical composition of the DP600 type of steel was done at the Laboratory of John von Neumann University, Kecskemét.

The dissertation contains two main fields, the experimental and simulation works, which are closely related to each other from the point of view of the presented research. For the simulations I got helped from the Technical and Economical University of Budapest, I have got the MSC.Marc&Mentat 2019 researcher licence for the FE simulations.

3.1. Experimental methods

In my dissertation the DP600 and AA6082 type of materials are in the focus of the research. For the research I have need the material properties of the applied materials, like flow curve and need static and dynamic tests, also. The DP600 was examined from several point of views. Firstly, for the microstructural examination was done, the specimens were grinded with 100-200-600 and 1200 μm grid papers, then polished with 3 μm diamond paste and lastly, etched with Nital (3%). The prepared specimens were analysed by a Carl Zeiss microscope, and an image recognition software helped to analyse the photos by statistically.

The static experiments of the clinched joints are equivalent with the spot-welded joints. In the present work the size of the sheets were 100x30x1 mm^3. For the tensile-shear and pull tests the specimen overlap was 30 mm. To perform the box test, holes were drilled to the sheets, which diameter were 16 mm.

In the literature the dynamic tests are carried about the high-speed tension [15] of the specimens which are the same as applied for the static tests, and fatigue tests. Clinched closed sectioned structures were tested with impact tests [16], and in [17] vibration tests were performed. The reason of the Charpy impact test was chosen for the dynamic tests is that I have not find any related literature. Two types of orientations were testes, the so-called normal and reversed, and according to the impact test results I found that the reverse orientation shows a ~15% higher absorbed impact energy. It could be useful for manufacturers to make cars safer.

On the cross sections of the joints, hardness tests were performed to analyse the effect of the forming on the hardening of the sheets. For the evaluation of hardness changing during forming, Vickers hardness tests were used (HV0.5 with 500 g load). The hardness tests were done on DP600/DP600 and DP600/DP800 heterogeneous joints also.

According to the literature a friction has a high impact on the final geometry of the joints, so I decided to analyse the tribological relations of the clinched joints as well.

3.2. Simulation methods

The second part of the dissertation is dealing with the finite element modelling related questions and the assessment of the results from numerical calculations. For the numerical simulations I have used the MSC.Marc&Mentat 2019 nonlinear finite element software.

During the simulations I tried to get back the measured values as good as possible, because the verified models are possibly able to simulate cases which cannot be or hardly possible to analyse by experimental methods. The main results from the simulations are the load-displacement curves and the characteristic "S" curves which shows the two sheet's interface after the simulations.

I have modelled and analysed the remaining geometry of the DP types of steels and in three different heat-treated conditions of the AA6082 type of aluminium alloy. I have analysed the frictional behaviour of the joints, and I have found similar results as the results of the experiments.

I have also deal in my dissertation with the simplified or equivalent modelling techniques of clinched joints. I have analysed the tensile-shear tests with an equivalent modelling technique and the box test with a simplified method. These methods are useful for analysts to evaluate a complex structure's response on different loads without the extremely high effort on calculating the proper geometry of the joints.

The effect of the tool's geometry was analysed numerically and experimentally, as well. The effect of the punching tool's geometry was analysed by the tools, manufactured by the Institute. For these tests, the aluminium alloy was selected, because of the less maximal forming force. Based on the numerical results a linear relationship I have derived for the estimation of the neck thickness. The equation has taken into consideration the tip radius and the conical angle of the punch. The estimated neck thickness can estimate further values, as the tensile strength of the hypothetic joint, which is beneficial on tool optimization procedures.

The examination of the dissimilar material joining is the dissertation's important part. I have analysed numerically the effects of the dissimilar thickness and dissimilar types of materials on the joints, like different strength DP steels and steel-aluminium joints. According to the results, dissimilar sheets influence the strength of the joints. The proper order of the sheets: thicker one, higher strength one should be the upper sheet. The derived relationships could be useful for the design engineers.

4. FURTHER RESEARCH POSSIBILITIES AND APPLICATION

During the writing of the dissertation, I have examined several important fields, based on the literature, of the clinched joints to make sure that the dissertation be the most comprehensive as possible. Because of the limits of the resources and the extent of the dissertation, many parts of the research can be continued.

In my dissertation I have not deal experimentally, nor numerically the interaction of the joints in complex structures, or the in-situ examining of the joints in operating structures, so these fields are also interesting to research in the future. The static and dynamic examinations of the joints in operating structures could be a possible future research material.

The chapter which shows the developed simplified model is valid for only tensile shear loaded cases. With further investigation the model can be extended for other main types of loads. And of course, the previously mentioned joints in operating structures could be also an interesting field of interests.

During the investigation of the joints between dissimilar materials I have derived the equation of the equivalent strength, which can consider the order of the sheets, in this particular case steel and aluminium. The resultant geometries and tensile shear values show good agreement in between the experiments and the numerically obtained ones. Further research is to test or extend the reliability of the equation for other types of dissimilar material joints. Based on the further research the form of the equation can be modified. In the literature the dissimilar materials mean a way lot more than the dissimilar metals, for instance the usage of plastic materials to join with metals. The possibility of these types of dissimilar materials can lead interesting results. In the future, it is possible to prove the numerical results of the joints of the dissimilar thickness sheets by experimentally.

The industrial usage of the results of my dissertation related to my workplace. The joints can replace the weldments of the frames of air supply units. During the writing of the dissertation there were no further steps to replace the welds.

The results of the impact tests can be used by the automotive industry during the design of the joints. It is possible to determine a main orientation of the crash and based on this orientation it is possible to use the so-called reversed orientation joints.

The further development of the simplified modelling technique for the industry is important from the point of view of the relatively simple usage of simulation of numerous clinched joints in operating structures and based on the results the response of the structures can be more precise, as well.

The most promising field of interest is the structural elements joined together with clinch joints in the automotive industry and the examination of these structures.

5. SUMMARY

In my dissertation, I have presented my work on clinched joints by experimental and numerical simulations.

I have started the research with an intensive literature review, to discover the field of clinching technology as deep as possible. In the first chapter, I have summarized the different clinching variants, technological methods, simplifications, and considerations for modelling.

In the literature review, I wrote about the questions of quality assurance, and I wrote the closely related background of the Theory of Plasticity.

After the literature review, I have presented the experimental work and its results on DP600 type of steel. In this chapter, I have presented the novel application of the Charpy-type impact tests on clinched joints. It has been proved that the “reverse” directional impacts show higher impact energy absorption compared to “normal” directional impacts. Based on the dynamic tests the optimal bottom thickness of the clinched joints was defined and with the optimal values, several static tests were performed.

On the cross-sections of the joints microscopical and hardness tests were performed, as well.

In the third chapter, using the cross-sections and the registered force-displacement curves the finite element model is calibrated. The calibrated model is used for further sensitivity analysis.

The simulation work was done mostly on steel sheets, but heterogeneous joints were also analysed. I have worked with aluminium material, as well. The different heat treatment conditions of the aluminium sheets were analysed experimentally and numerically, as well. Based on the test results of the aluminium joints, the heat treatment methodology has to contain the solvent annealing and a curing phase also to minimize the possibility of crack formation during the clinching process.

Based on the results of tensile loaded specimens I have developed a simplified or equivalent modelling method, which method could be useful for industrial applications after further development.

I have examined the effects of several variables on the joints, for example, the effect of the frictional behaviour between the sheets and the tools. The effect of the tribological characteristics of the process is analysed experimentally and numerically, and I have found that the simulations show similar results.

The applied material laws, which were generally used in sheet forming simulation related topics, were derived from material test results by the curve fitting method. The effect of the formulation of the material laws was analysed and compared through the geometrical parameters of the joints.

The geometrical effects of the die were analysed only through simulations, but the geometrical effects of the punching tool were analysed experimentally, too. Use of the FE results from the different punch tool geometry calculations and a mathematical method, a linear relationship was determined for the estimation of the neck thickness. The relationship is in between the tip radius and angle of the conical part of the punching tool. With the equation, the tensile strength of the joints also can be estimated. This part of the dissertation needs further research, but it is possible to take consider all the geometrical and material parameters for optimization.

I have analysed through simulations, based on literature data, the effects of the different DP steels on the clinched joints. The DP600 and DP800 types of steels were also examined experimentally.

The steel-aluminium dissimilar clinch joints were analysed. Based on the results of this case an equivalent strength was defined as a supplementary equation for analytical tensile strength estimation.

The results of my dissertation are cited in an article, deals with the possibilities of the FEA simulation of the clinch joints [18].

Budapest, August 2021

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6. NEW SCIENTIFIC REULTS

T1. I have proofed that the joints can reach ~15% higher absorbed energy during impact loading in reversed orientation on Charpy impact test machine. The explanation of the phenomenon is an upsetting process during the impact. [JSz 1][JSz 2][JSz 9][JSz 11].

T2. I have analysed the affecting parameters of clinched joints with a 2D axisymmetrical model and proofed that:

a. the anisotropy and the spring back effect negligible in case of DP600 type of steel [JSz 3],

b. the undercut is in relation with the unbuttoning load in case of box-test-like loads, and the relationship with bottom thickness is linear based on the simulation results of clinched joint made by DP600 type of steel [JSz 18],

c. experimentally and numerically proofed that the joint geometry depends on the heat-treatment condition of the AA6082 aluminium alloy [JSz 14][JSz 16],

d. proofed that the order of the dissimilar sheets is highly affect the strength of the joints, the proper order is: thicker one or, the higher strength one should be the upper sheet [JSz 12].

T3. I have experimentally and numerically proved that the tribological case of DP600 joints are affected the strength of the joints, as:

a. low values of frictional coefficient provide higher undercut (~15%) in between the sheets compare, which is beneficial from the point of view of box-test-like loads,

b. the frictional coefficient does not affect the neck thickness (~5%), which is important in tensile shear like load cases [JSz 12].

T4. I have developed an equivalent clinch modelling technique for tensile-shear case which is valid for DP600 type of steels. The proper choice of parameters of the equivalent model provides a high flexibility of the application of the model. Easy to apply in industrial environment. [JSz 17], [JSz 18].

T5. I have derived a supplementary equation in between DP600 and AA6082 dissimilar joint to extend the analytical estimation equation of the tensile-shear loads. The equation is dealing with the so-called equivalent strength parameter which depends on the order of the sheets. [JSz 14]

$$R_{m,eq.} = \begin{cases} \frac{R_{m,t1} + R_{m,t2}}{2}, if\ R_{m,t1} > R_{m,t2} \\ R_{m,t1} \cdot \frac{R_{m,t1}}{R_{m,t2}}, if\ R_{m,t1} < R_{m,t2} \end{cases}.$$

T6. I have derived a linear model for neck thickness estimation based on FE calculations and experimental results for AA6082 aluminium alloy. The equation is considering the punching tool’s tip radius and its conical angle [JSz 16]

$$t_{N,estimated} = 0{,}127 + 0{,}016\alpha + 0{,}098R.$$

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