

# Improving mechanical joining by increasing tool velocity

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## Abstract

In this article, the possibilities for improving the joining process of self piercing solid rivets and self piercing nuts by increasing tool velocity are demonstrated. Thereby, the focus is put on the joining process of high strength steel sheets. Proper and reliable joining of these steels presents a major challenge for mechanical joining techniques. In the conventional joining process, where tool velocities well below 1 m/s are common, different problems during the joining process caused by the high strength of the steel sheets can occur. At the punch riveting process undesirable material flow or unwanted burr development can occur, and at the setting process of self piercing nuts a deformation of the nuts is possible. These problems can be reduced significantly by using elevated tool velocity. In the present paper, characteristics of the joining process at conventional and elevated tool velocity are investigated. The influence caused by different tool velocities within the joining process is shown by cross section- and process force analysis. In the cross section analysis of the mechanical joints it is demonstrated that the quality of connections can be improved significantly due to the usage of elevated tool velocity. The process force analysis of the high speed joining process shows an oscillating progression of tools and joining elements.

## Introduction

When steel and aluminium materials are used for mixed construction, or thermal influences on workpieces will be prevented, mechanical joining methods are an excellent alternative to thermal joining methods. Recently, the selection of mechanical joining methods, in which premanufactured holes are not necessary for usage in state-of-the-art steels is very limited. The new high-strength steels have strength and therefore hardness characteristics that in some cases come close to or even exceed the characteristics of joining elements. This frequently causes problems during the process. This paper will focus on the influence of elevated tool velocity on the mechanical joining process with self piercing solid rivets and self piercing nuts as a new solution for the above mentioned problems.

## State Of The Art

Joining by forming summarizes joining methods where the connection is established by a local or entire forming of joining elements or workpieces. In general, the connections established by these methods are created through a local material forming whereby an interference lock of the workpieces is produced. In addition, a form closure through the joining process is established, in which the workpieces are elastically prestressed. Due to the combination of interference lock and force closure, high connection strength of the joints is established by joining by forming [1].

*Tab. 1: Advantages and disadvantages of mechanical joining [1]*

Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• No thermal structural transformation of workpieces and therefore neither distortion nor residual stresses nor embrittlement</li> <li>• Big variety of metallic and non-metallic materials and material combinations can be joined as well as different material thicknesses</li> <li>• High economic efficiency</li> <li>• Simple quality control mechanism</li> <li>• Materials with surface coatings can be joined without additional expenditure</li> <li>• Very good environmental behaviour</li> <li>• High process reliability</li> </ul>	<ul style="list-style-type: none"> <li>• Only lap joints possible</li> <li>• Lower tolerable static strain to e.g. welded joints</li> <li>• Geometrical unevenness due to nature of the process (local protrusions of the joining area)</li> <li>• Usually more difficult correction and repair of improper joints</li> <li>• Poor standardization and calculation methods</li> </ul>

The characteristic of joining with self piercing solid rivets is to produce permanent connections of sheet metal parts without premanufactured holes [2]. The piercing process is performed by a cylindrical solid rivet, and a two-sided accessibility to the workpieces is required. With punch riveting two or more workpieces can be joined. Important are the cutting capability of the material and a deformability of the die-side material. Because of the combination of interference lock and force closure, punch riveting connections have particularly at oscillating load significantly higher service life than thermal joined connections [3,4].

In the beginning of the process, the workpieces are fixed between die and the blank holder (FIGURE 1, I.). Afterwards, resulting from the movement of the punch, the rivet cuts a hole into the components and is subsequently pressed into the workpieces until the countersunk set head of the rivet is installed flush with the surface of the upper piece of the sheet metal (FIGURE 1, II.). In the third step of the riveting process, workpieces and rivet are jointly pressed against the die at a high level of force to indent the die into the lower sheet metal. This forms the material volume of the die-side sheet metal into the shaft groove of the rivet, which then creates interlocking (FIGURE 1, III.). A high level of ductility and a low level of material strength are beneficial for forming the lower piece of sheet metal into the rivet's shaft groove. Hence, the aluminium sheets are preferably arranged on the side of the die in case of steel-aluminium joints. The setting velocity is well below 1 m/s with conventional mechanical joining with self piercing solid rivets.

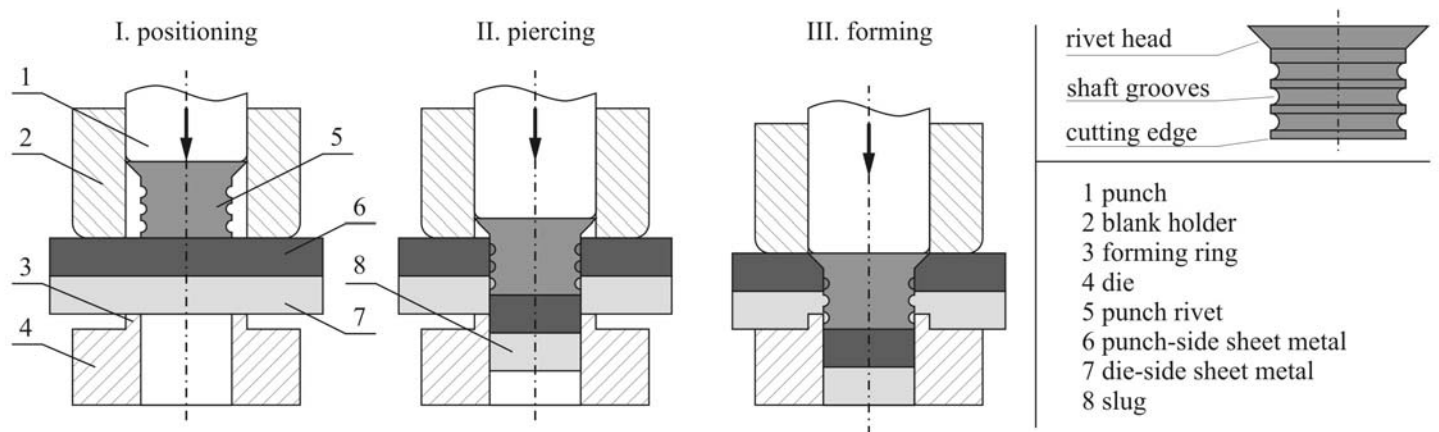


Fig. 1: Process steps - joining with self piercing solid rivets (schematic)

In the first step of the process, the sheets to be connected are pierced by the rivet as described, in order that the rivet functions as a punch. The necessary cutting force is supported against projection on the die on the lower piece of sheet metal. This is the reason why there might be an indentation in the elevation on the die in the lower

piece of sheet metal even before piercing the holes in the components, if there is a high level of cutting force caused by a high level of material strength in the steel sheet. Consequently, there is no possibility in the second process step to press a sufficiently large material volume into the rivet's groove. This might be the cause for poor quality of the joint as there is insufficient interlock between rivet and die-side sheet. Furthermore, small circular blanks (slug) are separated from the workpieces in the piercing process. This slug is discharged through the hole in the die. Sometimes, the upper slug has a larger diameter than the hole in the die, due to an improper piercing process of the high strength steel sheets (FIGURE 2, I.). The projecting burr is then sheared off on the cutting edge of the die while discharging these parts (FIGURE 2, II.) and is formed into the area of the rivets shaft groove in the further process routine (FIGURE 2, III.). The process described here produces joints at an unacceptable level of quality. Finally, the partially conic sheared edge can produce an undesired gap between the rivet and the punch-side sheet metal. This gap can impair the strength properties and corrosion resistance of the rivet connection [5].

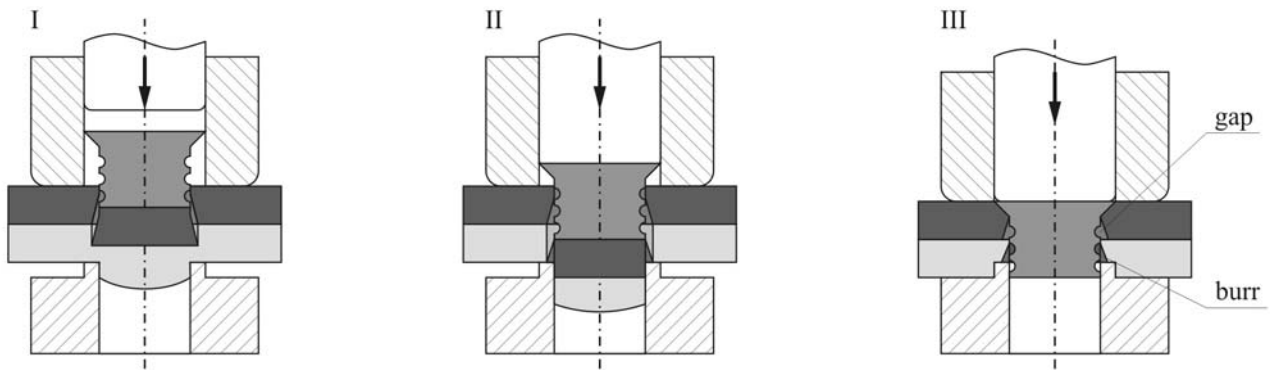


Fig. 2: Undesirable burr development during the joining with self piercing solid rivets (schematic)

Self piercing nuts are set without premanufactured holes into the sheet metal. After positioning the nut on the workpiece (FIGURE 3, I.) the sheet metal is pierced as the punch collar of the self piercing nut functions as punch (FIGURE 3, II.). The sheet is placed on a die with a hole through which the slug is discharged. After the successful piercing operation, a contour on the die is pressed into the sheet and thereby the clinch area of the nut is filled with material (FIGURE 3, III.). The process creates an interference lock and force closure connection between workpiece and nut. This connection enables the screwing of threaded elements into the assembly.

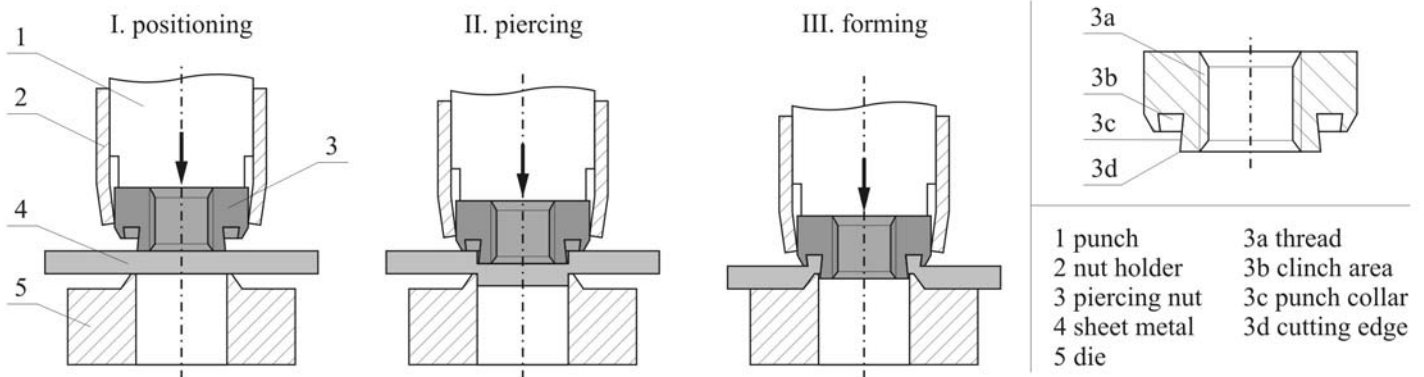


Fig. 3: Process steps - setting of self piercing nuts (schematic)

The described process sequence has the following requirements for self piercing nut and workpiece. First, the self piercing nut needs to have a sufficient hardness to limit a deformation of the nut during the piercing process. Plastic deformation of the nut during the setting process can lead to undesirable results, for example the thread of the nut loses its trueness to gauge size. Moreover, by compression of the punch collar the cutting gap is

reduced, in which the piercing process is compromised. In the second step of the setting process, forming of the sheet material into the clinch area of the nut is aimed. High flow stresses and partially low formability of the high strength metal sheets impede this process step.

To avoid these problems in the prior, only a few measures at the state of the art come in question. An increase of the self piercing nuts strength is limited, because the brittleness of the nut equally increases. Due to an increase of the brittleness, the properties of the connection, especially under dynamic loading, can be affected. Currently, alternative process systems are used for setting rivet nuts into high strength sheet metal. The holes are manufactured by laser cutting prior to the joining process. In addition, the system manufacturers (e.g. Arnold & Shinjo GmbH & Co. KG) are trying to adjust the geometries of the nuts and the parameter of the setting process to meet new requirements [6].

The selection of mechanical joining methods for use in steels with very high strength, where premanufactured holes are not necessary, is limited. The mechanical joining methods with the highest potential for usage are based on the process of piercing workpieces by a joining element (e.g. self piercing rivets, self piercing nuts). Therefore, a requirement is that the joining elements have a higher hardness as the workpieces, as this can cause damage to the joining element and improper connections. The new high strength materials have strengths and hardness properties, which are very close to or exceed in some cases strengths and hardness of the joining elements. An increase in hardness of the joining elements is limited, because that usually accompanies an increased brittleness. This can result in both, the joining process as well as the joint under load to an increased susceptibility to cracking. In addition, the partially altered material behaviour occurs while piercing the new high strength steels, which can also lead to undesirable results during the mechanical joining process with a cutting component.

As a solution to these problems increasingly the process dynamics at the mechanical joining are put into focus. For several years, research in various fields for usable effects by increasing the tool velocity is done by different research facilities. Main subjects of the investigations are the plastic strain rate and temperature dependent material properties in the joining process (FIGURE 4,5) as well as the inertial effects in the global structure. As an example, research activities related to nail elements for the joining of components are to be mentioned. These show that elevated tool velocity during mechanical joining can be advantageous compared to conventional tool velocity (tool velocity significantly lower than 1 m/s) [7,8,9,10,11]. Other examples of useful effects on mechanical joining at elevated tool velocity are presented in [12]. In the literature, the term "high speed joining" is used to describe processes with a tool velocity range of about 5 m/s to 100 m/s. The characteristics of the different joining processes have an important influence on the potential for usage of elevated tool velocity. For example, semi-tubular self pierce riveting of aluminium compounds with a flat anvil at elevated tool velocity illustrated advantages compared to the usage of conventional tool velocity. In contrast, the semi-tubular self pierce riveting of steel sheets at tool velocity of about 10 m/s compared to conventional tool velocity in some cases can be a disadvantageous [12]. First studies showed that joining with self pierce solid rivets at elevated tool velocity has a very high potential, especially for joining aluminium compounds with high strength steel sheets. The main advantage lies in improved results during the piercing process in which the components are punched by the solid rivet [13].

Based on the research findings at the Fraunhofer IWU, the focus for mechanical joining at elevated tool velocities was placed on joining methods with a high proportion of cutting. This includes joining with self piercing solid rivets as well as setting of self piercing nuts. The aim of the research activities presented in this article is to demonstrate the possibility to extend the process limits of punch riveting and setting of self piercing nuts by usage of elevated tool velocities, especially in the area of steel sheets with a very high strength.

In the following investigations, tool velocities of about 5 to 10 m/s are considered as high speed joining process, while tool velocities in conventional joining applications in mechanical joining are well below 1 m/s. In FIGURE 4 the results of numerical investigations are shown with the help of finite element method. In this example, piercing of sheet metal (steel; thickness: 2 mm; diameter of punch: 5 mm) with several tool velocities

is considered. In consequence of higher tool velocity, the piercing process is done with higher strain-rates (FIGURE 4), which can cause a higher flow stress and a reduced ductility of the steel material.

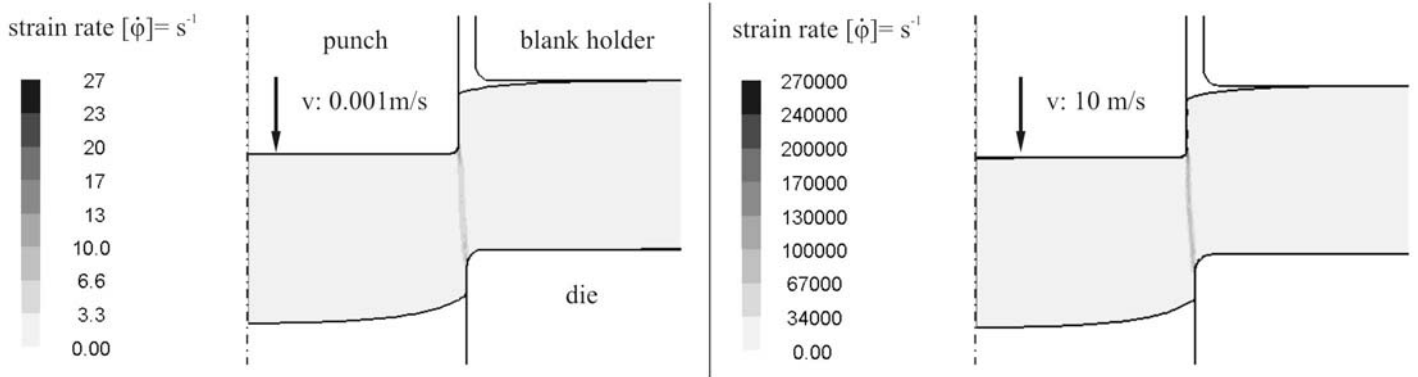


Fig. 4: Strain rate in the cutting zone while piercing sheet metal with several tool velocities (FEM model)

At the same time, temperature is raising in the cutting zone with higher tool velocity. While piercing the sheet metal with conventional tool speed thermal conduction occurs, so that there is no significant increase in the workpieces temperature in the cutting zone. With increasing tool velocity, less heat is transported because of the time-dependency of thermal conduction. The result is a very small volume with high temperature, up to the melting point of the metallic material [14,15].

These two effects, strain-rate-dependend hardening and temperature-dependend softening, influence each other contrarily and depend on the material that is pierced. When piercing the material, only a very small volume is affected, the so called shear band. Piercing ductile material with a high tool velocity causes a fine-grained fracture surface, comparable with a brittle fracture zone [14].

In FIGURE 5 the temperature dependence in the cutting zone of tool velocity of sheet metal using FEM simulation is shown. The boundary conditions are defined as follows: no heat exchange between sheet metal and tools occurs and 95% of the forming work is transformed into heat. When piercing the material with a velocity of 0,001 m/s, heat is transported by thermal conduction almost completely so that there is a maximum temperature of only 33 °C in the cutting zone. Considering higher tool velocities of 5 m/s and 10 m/s, a temperature of 570 °C respectively 610 °C can be observed.

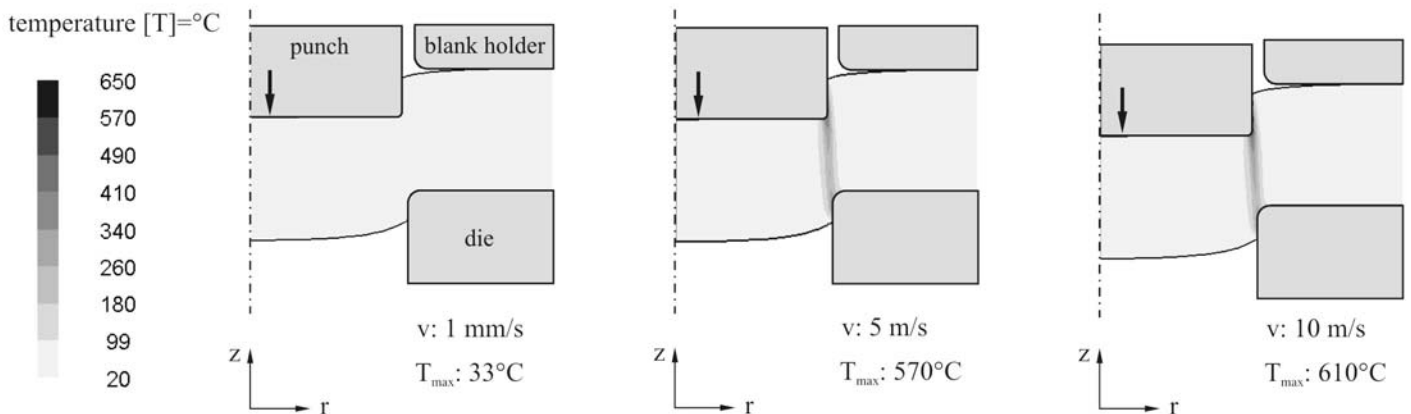


Fig. 5: Temperature in the cutting zone while piercing sheet metal with several tool velocities (FEM model)

Most of the results presented in this article were produced with a high speed joining machine using a pneumatic actuator (FIGURE 6). The structure of the machine is based on a four-column frame. The drive consists of an impact cylinder and an impact weight, which is mounted on the piston rod of the cylinder. During the joining process, the impact weight applies to the guided punch holder, which transmits the pulse over the punch to the joining element. This joining machine reaches impact speeds between the impact weight and the punch up to 15 m/s. However, the impact speed can be regulated by a precision pressure regulator system. The upper part of the machine can be lifted and lowered for inserting the joining elements or workpieces and replacement of the punches by pneumatic cylinders.

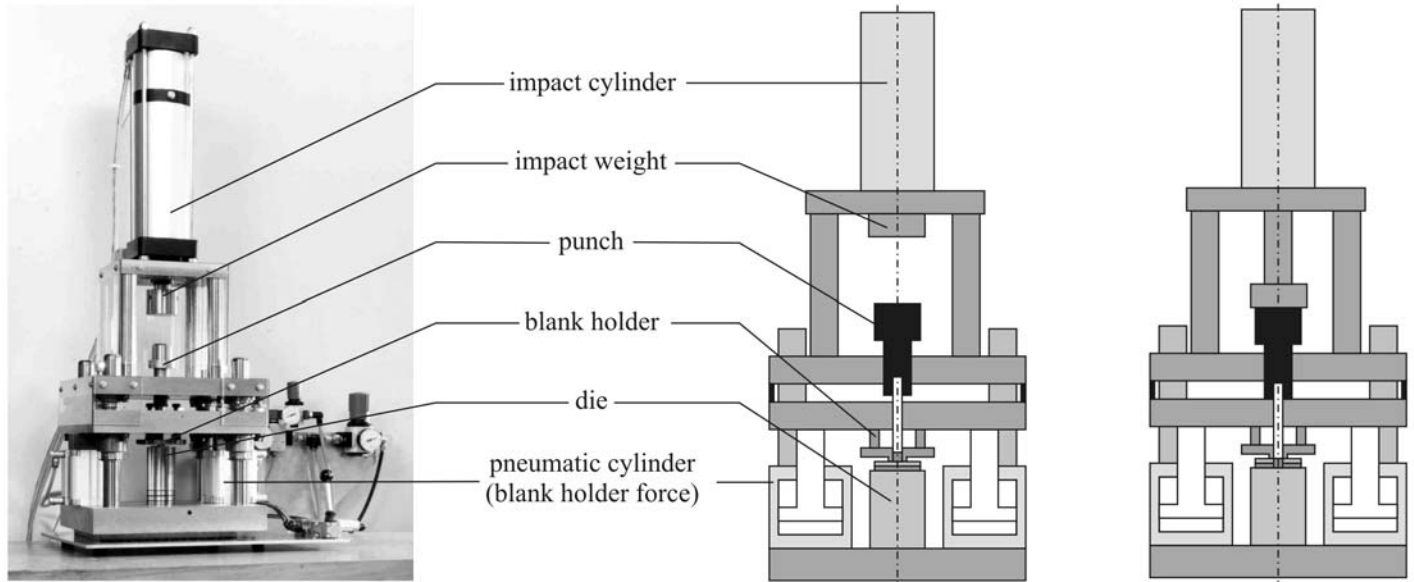


Fig. 6: Structure of the pneumatic high speed joining machine

The forces and the motion profile of the high speed joining process were analysed by using a drop tower because it is easier to access, and the velocity of the drop weight can be adjusted more accurately. Furthermore, a piezoelectric load cell positioned below the die was used for recording the process forces. The joining process was recorded with a high-speed camera which was directed at the contact zone between the drop weight and the punch at a frame rate of 100.000 fps. Measuring marks were put on drop weight and punch. After calibrating the picture material, it is possible to determine the motion profile of the two tools. The drop weight with a mass of 5.8 kg can be accelerated up to 18 m/s by the drop tower (FIGURE 7).

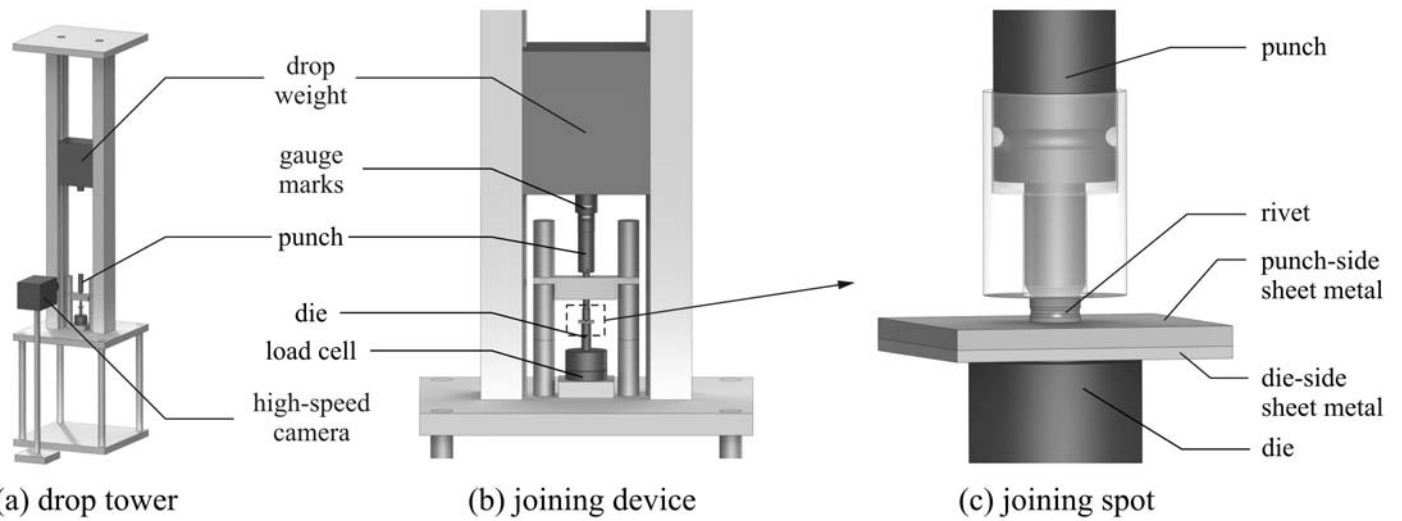


Fig. 7: Test setup - drop tower for process analysis

As tests on various connections indicate, it is possible to counter early die indentation into the die-side sheet metal as well as the occurrence of an undesired burr by increasing the tool velocity. In FIGURE 8, the cross sections of three connections are presented, to show the influence of elevated tool velocity on the connection quality. The cross sections of FIGURE 8 on the left-hand side in these comparisons show the results of the conventional joining process. The sections of the figure on the right-hand side show the results of elevated tool velocities in a range of as much as 5 m/s. It can be shown that the described problems of lacking interlock and burr formation can be reduced significantly when joining with increased tool velocity. Especially in the cross section comparison of connection c, in which a press-hardened boron steel (max. tensile strength circa 1600 MPa) is joined at different tool velocities with an aluminium alloy, the differences are visible.

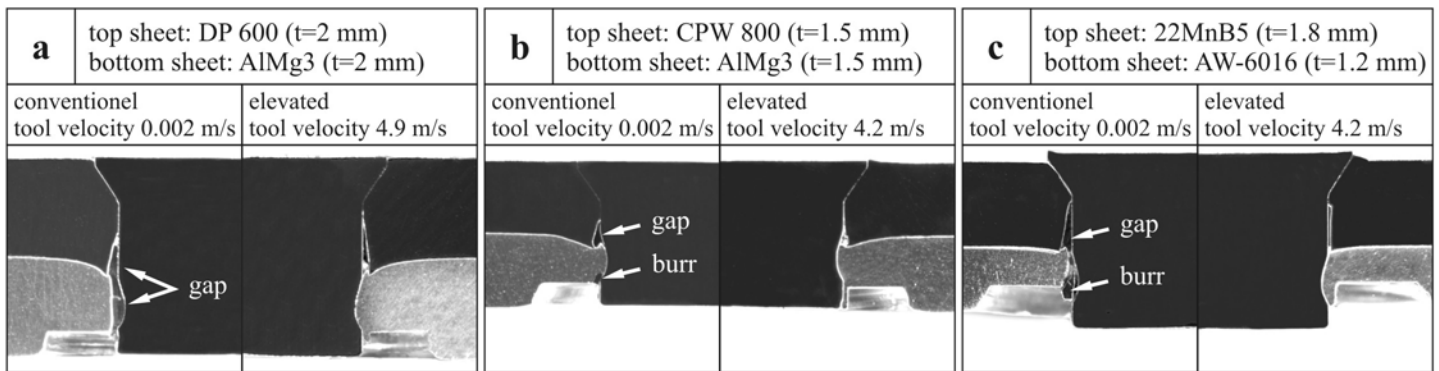


Fig. 8: Comparison of the with different tool velocities joined punch riveting connections (cross sections)

An analysis of this process has the purpose of supplying information about the process forces during joining. The here presented process force curve is caused by the high speed punch riveting process of the above mentioned connection c (FIGURE 8) using a drop tower (FIGURE 7). The curves in FIGURE 9 indicate the changes in the process force over time. Several test series were used to prove that these changes could be reproduced and a representative set of curves was selected in FIGURE 9. These data indicate that the process lasted about 2 ms and the process force had an oscillating course. One of the reasons for these oscillations was the fact that the drop weight and punch were in contact several times during the whole the process. During the first step of the process, forces in the range of circa 40 kN were measured. These forces can be assigned to the piercing process (FIGURE 1, II.). In the further progress, the rivet is impacted into the cut hole at a low level of force. The third step is characterized by a rise of circa 50 kN of the occurring forces that should be assigned to

the die indentation into the die-side sheet metal and pressing the countersunk set head of the rivet into the punch-side sheet metal (FIGURE 1, III.).

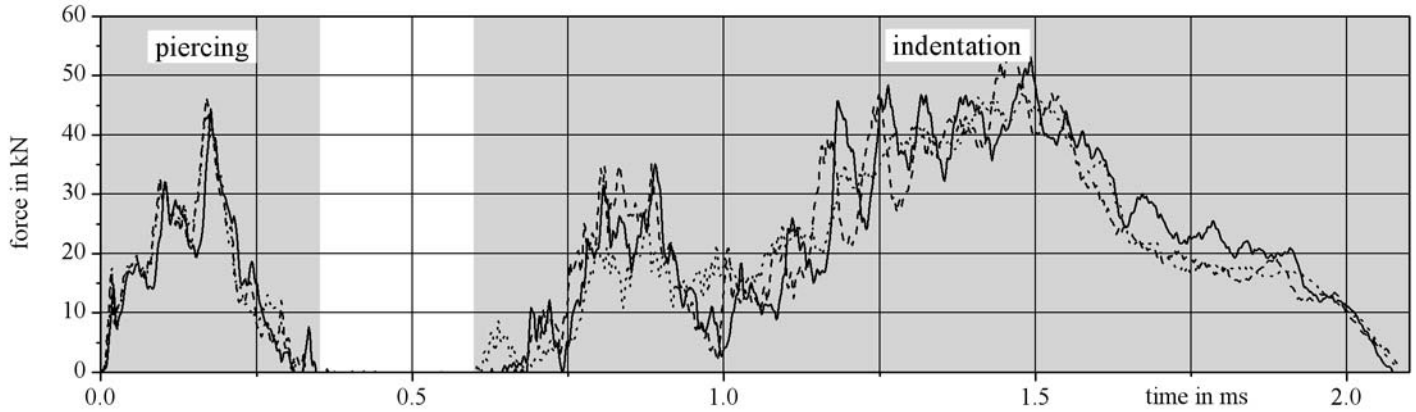


Fig. 9: Process forces of joining with self pierce solid rivets at elevated tool velocity

The influence of tool velocity on the setting process of self piercing nuts is shown on various examples. At first the influence of tool velocity on the compression of the self piercing nuts, set into a press-hardened 22MnB5 sheet material ( $t = 1.5$  mm, max. tensile strength = 1600 MPa), is investigated. At the tests with conventional tool velocity, modified self piercing nuts of sizes HN5 / HN6 (M5 / M6 thread, Arnold & Shinjo GmbH & Co. KG) were pressed with a tool speed of 5 mm/s into the sheet until the completion of the piercing process. For the test with conventional tool velocity an electro-mechanical press was used. The axis feed of the press was stopped immediately after the piercing process in order to avoid indentation of the die ring and a deformation of the cutting surface of the sheet metal.

At the pneumatic high speed joining machine (FIGURE 6), equally a setting pressure was set, at which the self piercing nut only pierces the sheet, but the indentation of die ring into the sheet is avoided due to excess energy. The speed of the impact weight in this process was about 3.7 m/s. The height of the self piercing nut before and after the setting process was measured in order to determine the compression. In addition, the trueness to gauge size of the nut thread before and after the setting process was verified. The diagram (FIGURE 10) shows the correlation between the compression of self piercing nuts and the applied tool velocity. The nuts set at elevated tool velocity show a lower compression compared to those nuts set at conventional tool velocity. At both sizes of the self piercing nuts set with a tool speed of 5 mm/s, the function of the nut thread was no longer given after the piercing process. In contrast, the threads of the nuts set at elevated tool velocity provided correct function after the piercing process. The experimental results show the potential of high speed joining to reduce the compression of the nut when it is used on high strength steel sheets.

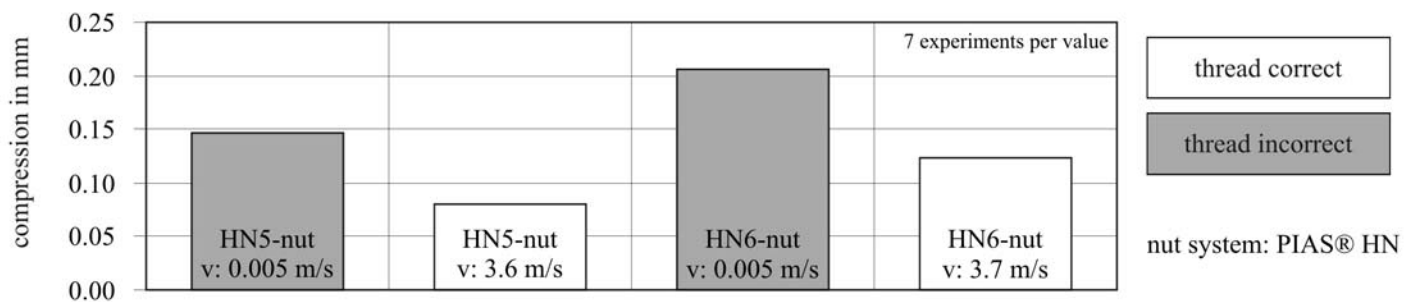


Fig. 10: Influence of the tool velocity on the compression of the self piercing nut (example for 22MnB5,  $t = 1.5$  mm)

The connection between self piercing nut and sheet metal must meet minimum requirements in terms of resistance to rotation during the subsequent screwing of a threaded element (twisting torque) and the pull out

resistance (against the setting direction). Therefore, an undercut is created by the forming process after piercing the sheet material. The resulting interference lock and force closure between the nut and the sheet metal is additionally supported by a knurling on the outer surface of the punch collar.

The cross section in FIGURE 11 shows the comparison of a modified HN5 self piercing nut, which is set into steel sheets with different strengths at the same setting force 50 kN. At the connection with the soft metal sheet (FIGURE 11, left) the clinch area could be completely filled with material. In Contrast, the connection with the high strength steel shows a lower filled clinch area and a deformation of the self piercing nut. At this example, the process limits for conventional self piercing nut systems are visible, in which the clinch area of the nut is adjusted to materials whose strength and ductility allow proper filling of the element contour. The current field of application of the investigated nut system is limited to materials with a maximum tensile strength of 850 MPa. For steel sheets that exceed this tensile strength, new geometries for the self piercing nuts need to be developed. The objective of this research therefore is the development of alternative self piercing nut geometries that are appropriate for steel sheets above the mentioned strength limit. Therefore, the so far proven strength classes of nuts should be retained. Also a massive increase of setting forces to achieve a better forming of steel sheets must be avoided in order not to impair the service life of dies.

The cross section (FIGURE 11, right) shows undesired deformations of the nut, and insufficient undercut formation occur when setting conventional self piercing nuts into high strength steel sheets. Only partial contact between self piercing nut and sheet metal can be observed.

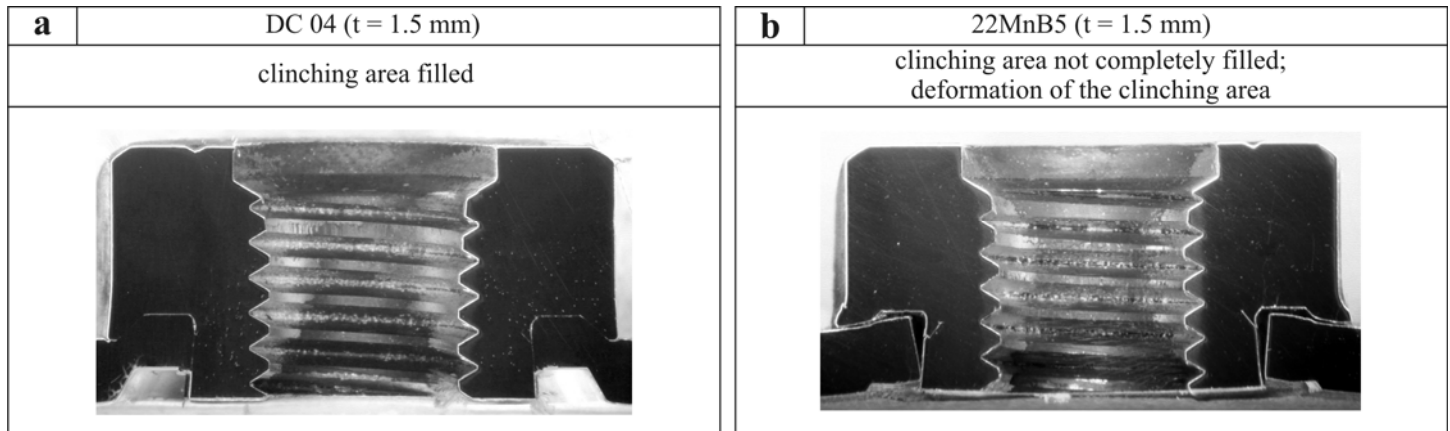


Fig. 11: Examples for self piercing nut - sheet metal connections; left: soft metal sheet (DC04), right: high strength sheet metal (22MnB5)

To maximize the contact surface between nut and sheet metal, the shoulder of the clinch area is removed by machining at the modified self piercing nuts. This is intended to achieve a support of the sheet metal in the axial direction to the nut directly after the piercing process. Immediately after the piercing operation, a radial flow of material in direction to the punch collar is generated. Due to the conically and knurled shape of the punch collar, a clamping effect between the sheet metal and the punching collar of the nut can be achieved.

The cross sections (FIGURE 12) show the joining results for the modified self piercing nuts of sizes HN5 / HN6 set at elevated tool velocities. A sufficient contact surface between the punch collar of the nut and the sheet metal, necessary for the above mentioned clamping effect, is achieved. A comparison to conventional set nuts is not possible due to high compression of the nuts during conventional setting process.

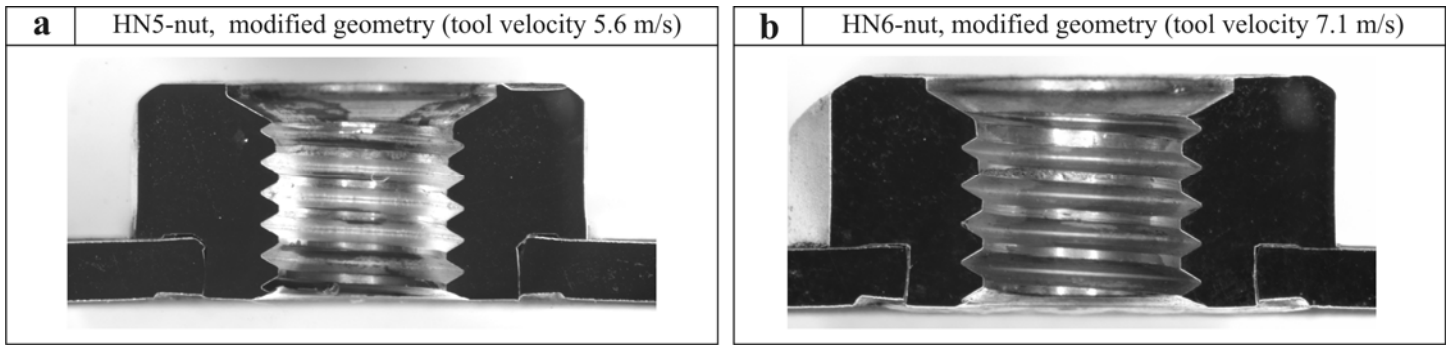


Fig.12: Self piercing nut - sheet metal connections with modified self piercing nut geometry (sheet metal: 22MnB5,  $t = 1.5$  mm)

To examine qualities of connections shown in the cross sections above, an investigation of the connection properties was made. On the one hand, the pull out force required to pull the set self piercing nut in the opposite setting direction was measured. On the other hand, the maximum twisting torque was measured, which the nut can transfer at a test with a torque wrench. The results of these tests were compared to the minimum requirements for self piercing nut - sheet metal connections. The evaluation of the achieved pull out forces and twisting torques (FIGURE 13) show that the connections with the modified self piercing nuts, joined at elevated tool velocity, exceeded the minimum requirements.

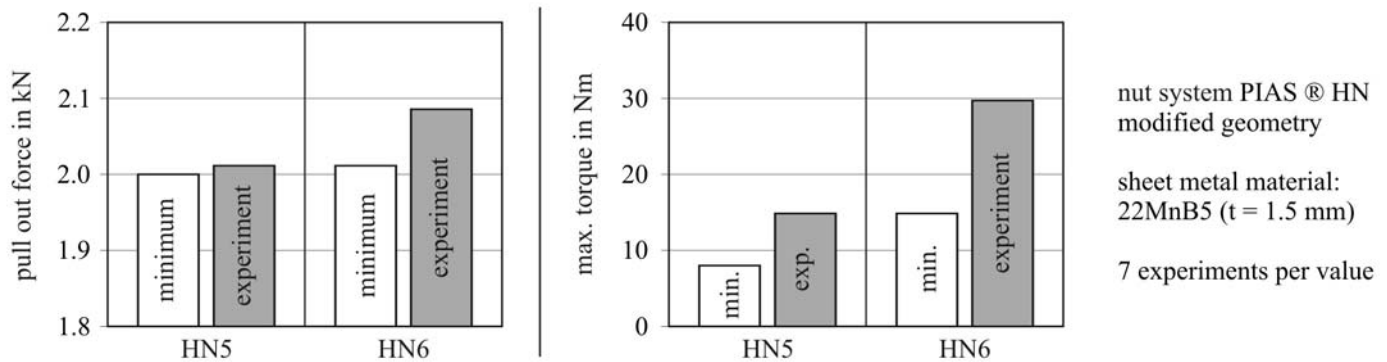


Fig. 13: Properties of the self piercing nut - sheet metal connection, joined at elevated tool velocity

## Conclusion

The experimental results on mechanical joining at increased tool velocities presented in this paper indicate a great potential for joining high strength steel. For the punch riveting process it was shown that the undesired effects of early die indentation into the lower piece of sheet metal and burr formation can be avoided by increased tool speed. At the setting of self piercing nuts it can be established that due to the combination of geometry modification of the nut and increasing the tool velocity, improved properties of nut-sheet metal connection can be achieved by the usage at high strength steel sheets. Based on the above shown analysis of the mechanical joining processes it can be detected that the improvements achieved by the increased tool velocity are mainly justified in the piercing process of the high strength steel.

In following investigations, it will be necessary to research the causes of the speed-sensitive effects in more detail. In addition, investigations on joining at elevated tool velocities of other materials besides high strength steel, e.g. fiber-plastic composites, are intended. Other subjects of further research will be the development of element geometries appropriate for joining high strength steel sheets and the analysis of the influence of elevated tool velocity on the joining machine. At the high speed joining process, loads with impacts on the tools occur. The influence of these stresses must be investigated in the context of service time studies of the tools. Aim of this investigation is the substitution of energy intensive pneumatic drives, which are currently mainly used in high speed joining machines. In cooperation with industrial partners like Promess GmbH and Arnold &

Shinjo GmbH & Co. KG currently an electromechanical drive is tested at the Fraunhofer-Institute for Machine Tools and Forming Technology IWU.

## REFERENCES

1. K. Grote and E. Antonsson, „Springer Handbook of Mechanical Engineering“, Springer Verlag, Berlin, 2009.
2. L. Budde and R. Pilgrim, „Stanznieten und Durchsetzfügen“, Die Bibliothek der Technik. Bd. 115. Landsberg/Lech, Verlag Moderne Industrie, 1999.
3. O. Hahn and U. Klemens, „Fügen durch Umformen, Nieten und Durchsetzfügen - Innovative Verbindungsverfahren für die Praxis“, Dokumentation 707 der Studiengesellschaft Stahlanwendung e.V., Düsseldorf, 1996.
4. O. Hahn and A. Peetz, „Untersuchungen zur Fertigung sowie zum Festigkeits- und Alterungsverhalten hybrid gefügter Aluminiumfeinbleche am Beispiel Stanznieten-Kleben“, Aachen: Shaker Verlag, 2001.
5. R. Neugebauer, F. Jesche, C. Kraus and S. Hensel, „Mechanical joining with self piercing solid-rivets at elevated tool velocities“, International Conference on Material Forming 2011, Belfast, 2011.
6. U. Wohlfahrt, R. Neugebauer, R. Mauermann, C. Kraus and T. Kropp, „Hochgeschwindigkeitsfügen von Verbindungselementen in hoch- und höchstfeste Stähle“, Arnold & Shinjo GmbH & Co. KG, Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik, EFB-Kolloquium Blechverarbeitung 2011, Bad Boll, 2011.
7. M. Dreher, U. Füssel, V. Johne, J. Amedick and P. Wiethop, „Stanznageln - mechanisches Fügen hochfester Blechwerkstoffe“, In: lightweightdesign 03/2009, Vieweg+Teubner Verlag / GWV Fachverlage GmbH, Wiesbaden, 2009
8. O. Hahn and T. Draht, „Entwicklung des Bolzensetzens für Blech-Profil-Verbindungen im Fahrzeugbau“, LWF Schriftenreihe. Berichte aus dem Laboratorium für Werkstoff- und Fügetechnik, 2006.
9. T. Draht, D. Hußmann and G. Meschut, „Hochgeschwindigkeits-Bolzensetzen RIVTAC - Mechanisches Fügen im Intermezzo der Werkstoffe“, Intermezzo der Werkstoffe: Die Chance der Wahl für Konstrukteure und Planer, EFB-Kolloquium Blechverarbeitung 28, in: Tagungsband, Europäische Forschungsgesellschaft für Blechverarbeitung Band 29, Hannover, 2008.
10. O. Hahn and S. Poßberg, „Entwicklung des druckluftbetriebenen Bolzensetzens für den Einsatz im Karosserierohbau“, LWF Schriftenreihe, Berichte aus dem Laboratorium für Werkstoff- und Fügetechnik, 2008.
11. O. Hahn and D. Hußmann, „Weiterentwicklung des Bolzensetzens für innovative Fahrzeugkonzepte des automobilen Leichtbaus“, LWF Schriftenreihe, Berichte aus dem Laboratorium für Werkstoff- und Fügetechnik, 2008.
12. R. Neugebauer, C. Kraus, O. Hahn and G. Leuschen, „Anwendungsuntersuchung zum Impulsfügen mit Halbhohlstanzniet“, EFB-Forschungsbericht 286, Europäische Forschungsgesellschaft für Blechverarbeitung e.V.-EFB, Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik -IWU, Chemnitz ; Univ. Paderborn, Freundeskreis des Laboratoriums für Werkstoff- und Fügetechnik, Hannover, 2008.
13. C. Kraus, „Hochgeschwindigkeitsfügen mit Vollstanzniet“, EFB-Forschungsantrag vom 15.4.2010: Aktenzeichen 02/110, Europäische Forschungsgesellschaft für Blechverarbeitung e.V.-EFB, Hannover, 2010.
14. L. Krueger, „Untersuchungen zum Festigkeits-, Verformungs- und Versagensverhalten der Legierung Ti-6-22-22S in Abhängigkeit von der Temperatur, der Dehngeschwindigkeit und dem Spannungszustand“, Dissertation, TU Chemnitz, 2001.
  - A. Shawky, „Verformungs- und Versagensverhalten ausgewählter niedrig legierter Stähle unter Variation von Temperatur, Verformungsgeschwindigkeit und Spannungszustand“, Dissertation, TU Chemnitz, 2006.