Development and Evaluation of Alternative Materials for Friction Stir Welding of Steel

Friction Stir Welding (FSW) was developed in 1991 at The Welding Institute (TWI) in Great Britain, and has become a widely used method of welding aluminium and copper structures. The method is based on a simultaneous application of pressure and friction which generates heat that leads to the softening of the join parts to be welded. Due to stirring the tool in the softened metal the connection of the components is ensured, as shown in Fig. 1. Besides the resulting high quality of the welds, FSW offers a multitude of advantages as the ability to join materials that are difficult to fusion weld, for example aluminium alloys, magnesium and copper as well as a good suitability for automation and adaptability for robot use. Due to low distortion and shrinkage even in long welds, excellent mechanical properties in fatigue, tensile and bend strengths can be achieved. In contrast to conventional processes, no arcs or fumes are produced, which is beneficial for health and environmental protection aspects. The welding process shows due to the lack of need for welding consumables and auxiliaries high potential for saving resources and energy. From an environmental point of view, it can be noted that FSW produces less waste in the form of slag, weld residue, pretreatment, etc., as compared to molten welding processes, and thus does not result in environmental stress from contained alloying elements, i.e. expensive recycling processes are not required [1, 2].

As a potential group of users, in particular shipbuilding, vehicle construction and general steel construction, can be seen, in which long welds of large-area components and structures are prefabricated in assembly halls. Through the use of friction stir welding, the production costs of welds due to the shorter joint preparation and post-processing times, faster welding speeds can be drastically reduced, and thus competitiveness is increased. Numerous investigations have already examined the transferability of FSW to the welding of steel structures. Besides conventional construction steels, the principle of weldability has been demonstrated on various steel systems as austenitic steels, dual phase steels and stainless steels. Here, the sheet thicknesses that could have been welded amounted to up to 20 mm in a single-layer process [3–13]. During the welding process of steel, the tool is subjected to extremely high tem-

Keywords
friction stir welding, Al_2O_3, ZrO_2, SiC, Si_3N_4

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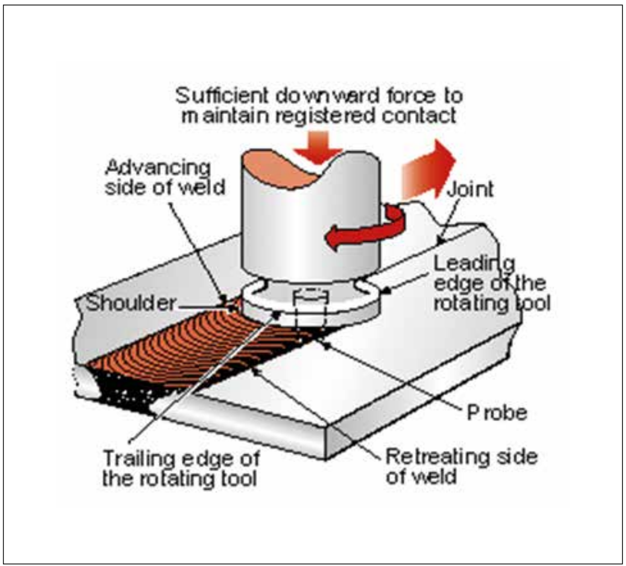

Fig. 1
Scheme of the operating principle of FSW

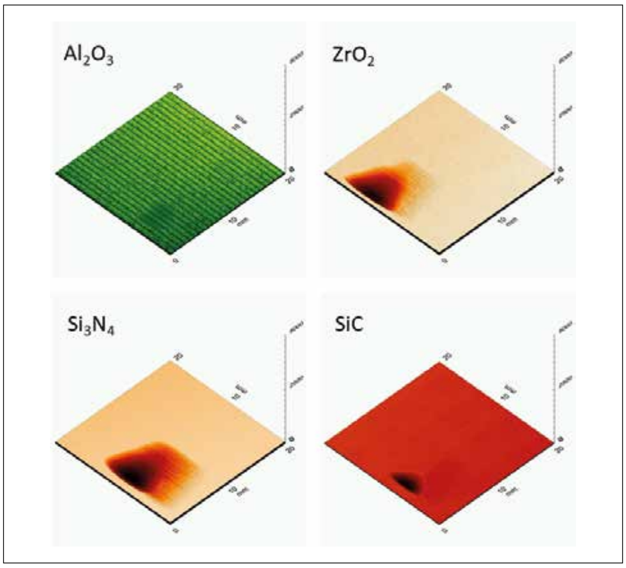

Fig. 2
Determination of the wear resistance of the respective ceramic materials against steel

peratures of approximately 1200 °C and corrosive and abrasive wear. Therefore, the requirements for mechanical, chemical and tribological resistance at high temperatures demand material systems with outstanding properties. Thus, occurring stresses of the tool and its interaction with the workpiece to be welded is of particular importance.

The current standard is, in addition to special alloys (e.g. tungsten-rhenium, tantalum base materials) and solid carbides, the use of pcBN tools (polycrystalline cubic boron nitride). While metallic tools do not show sufficient wear resistance, pcBN, due to its atomic structure, has a very high hardness and excellent wear resistance, but also shows the brittleness that is common for ceramic hard materials, increasing the risk of fractures during use under overload. Moreover, as a consequence of high raw material and production costs and a limited number of manufacturers, the availability of tools for the FSW of steels is insufficient [14, 15].

Hence, in course of the present work, common ceramic materials are to be tested, in order to find a more economical and adequate replacement for pcBN-tools. Ceramic material systems have already proven their application potential and in particular their cost-effectiveness in many areas of steel production and processing. From the materials used in the field of smelting metallurgy in the lining of blast furnaces and casting machines to high-performance cutting tools, the performance of ceramic materials in interaction with steel has been demonstrated.

Experimental results

For the experimental setup, the following materials were used as tool material: Al_2O_3, ZrO_2 (both BCE Special Ceramic GmbH/DE), SiC and Si_3N_4 (both FCT Ingenieurkeramik GmbH/DE).

The respective material properties can be found in Tab. 1. In case of tested steels, the unalloyed steel S235JR / 1.0038 as well as the austenitic stainless steel X5CrNi18-10 /1.4301 were used.

For the determination of the wear resistance of the respective tool material against steel, a tribology test stand, equipped with a steel disk with a diameter of 200 mm, a rotating speed of approx. 120 rpm and a contact force of 10 N was used.

The contact time between steel and ceramic material amounted to 2 h, in order to overcome the detection limit. For the quantification of wear, an optical profilometer, based on a chromatic, white light

Tab. 1
Material properties of the tested ceramics

Material property	Al_2O_3	ZrO_2	Si_3N_4	SiC
Fracture toughness [MPa · √m]	4,3	7	6	3,5
Hardness [MPa]	1800	1200	1600	2600
Bending strength [MPa]	340	500	990	400
Poisson number [–]	0,22	0,3	0,26	0,15
Young's modulus [GPa]	380	200	320	400
CTE RT-1000 °C [10^{-6} K^{-1}]	8,5	10,5	3,0	4,5
Thermal conductivity [W/m·K]	30	2	30	140
Thermal shock parameter R2 [W/m]	0,0025	0,0003	0,0229	0,0264

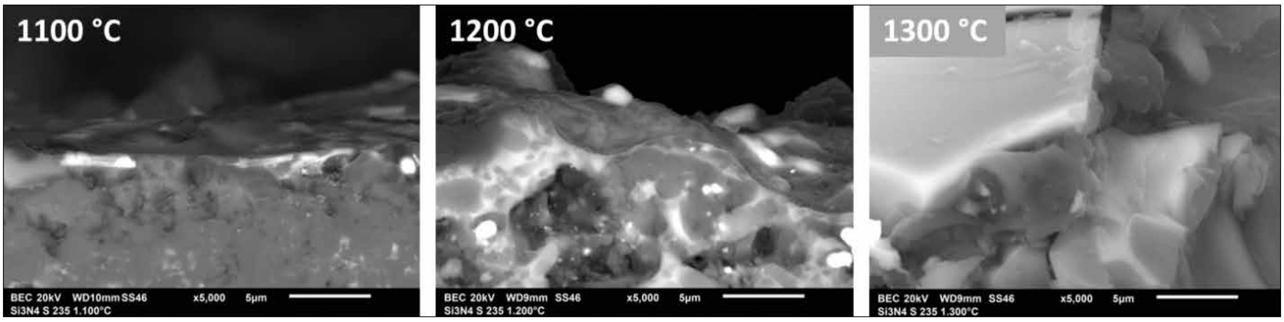

Fig. 3
Influence of the temperature on the thermochemical resistance of ceramic tool materials against steel at the example of Si_3N_4 and construction steel S235JR

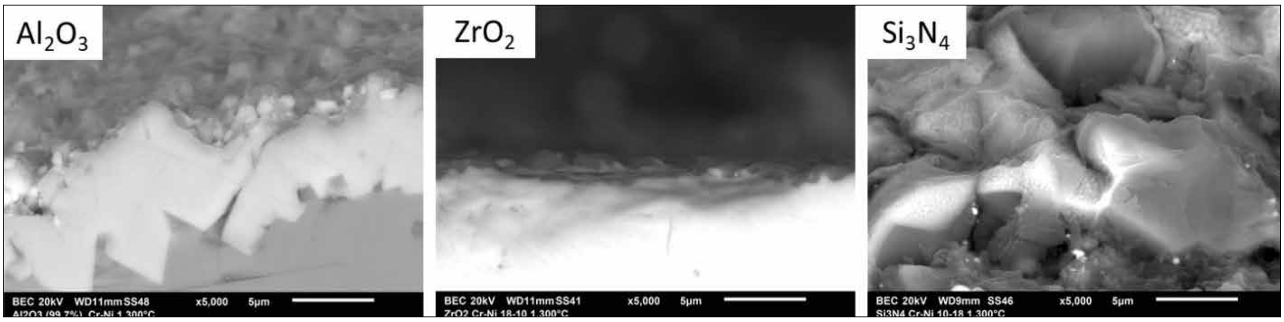

Fig. 4
Influence of the ceramic material on the thermochemical resistance against steel at the example of 1300 °C and austenitic stainless steel X5CrNi18-10

Fig. 5
Experimental setup for test under realistic conditions with FSW-machine (HLR Systems/DE, l.), tool holder including Si_3N_4-tool (middle), and test route (r.)

measurement, was used. The results of the tribology test can be seen in Fig. 2.
It shows that in good agreement with e.g. the hardness, the materials are subject to different wear.
Hence, alumina as well as silicon carbide show a promising resistance towards wear, due to steel. In contrast, the less hard zirconia and silicon nitride show more pronounced tribologically related effects. During FSW process the tool suffers from, besides those tribological stresses, thermally induced wear. Therefore, the determination of the resistance of the ceramics against steel at elevated temperatures took place at 1100, 1200 or 1300 °C, respectively.
The different steel and ceramic combinations were realised by putting them on top of each other without the application of any additional forces within the furnace. Under oxidising atmosphere, the dwell time amounted to 5 h. The influence of the temperature on the thermochemical resistance of ceramic tool materials against steel at the example of Si_3N_4 and construction steel S235JR is depicted in Fig. 3. It shows that the reactivity between steel (solid state)

and the respective ceramic materials increases with increasing temperature.
This trend could be observed in case of every combination, irrespective of kind of steel as well as of ceramic material. Fig. 4 indicates the great influence of the ceramic material on the thermochemical resistance against steel.
As can be clearly seen, the reaction zone is much less pronounced in case of oxidic tool materials. In contrast, the silicon nitride shows deep penetration zones, favouring thermomechanical wear of the tool during operation. The SiC sample led to the formation of silicides and the reduction of the melting point of the steel already at 1200 °C, and therefore proved to be inadequate.
After the pre-evaluation, the respective tool materials were tested under realistic conditions. Therefore, the experimental setup, shown in Fig. 5, was used, which included a FSW-machine (HLR Systems/DE), the tool holder as well as test steel sheets, made of either S235JR/1.0038 or X5CrNi18-10/1.4301 with a dimension of 200 mm × 200 mm × 6 mm. The welding parameters were a contact force of approx. 25 kN, number of revolutions of 670 rpm and a feed motion of 5 mm/s.

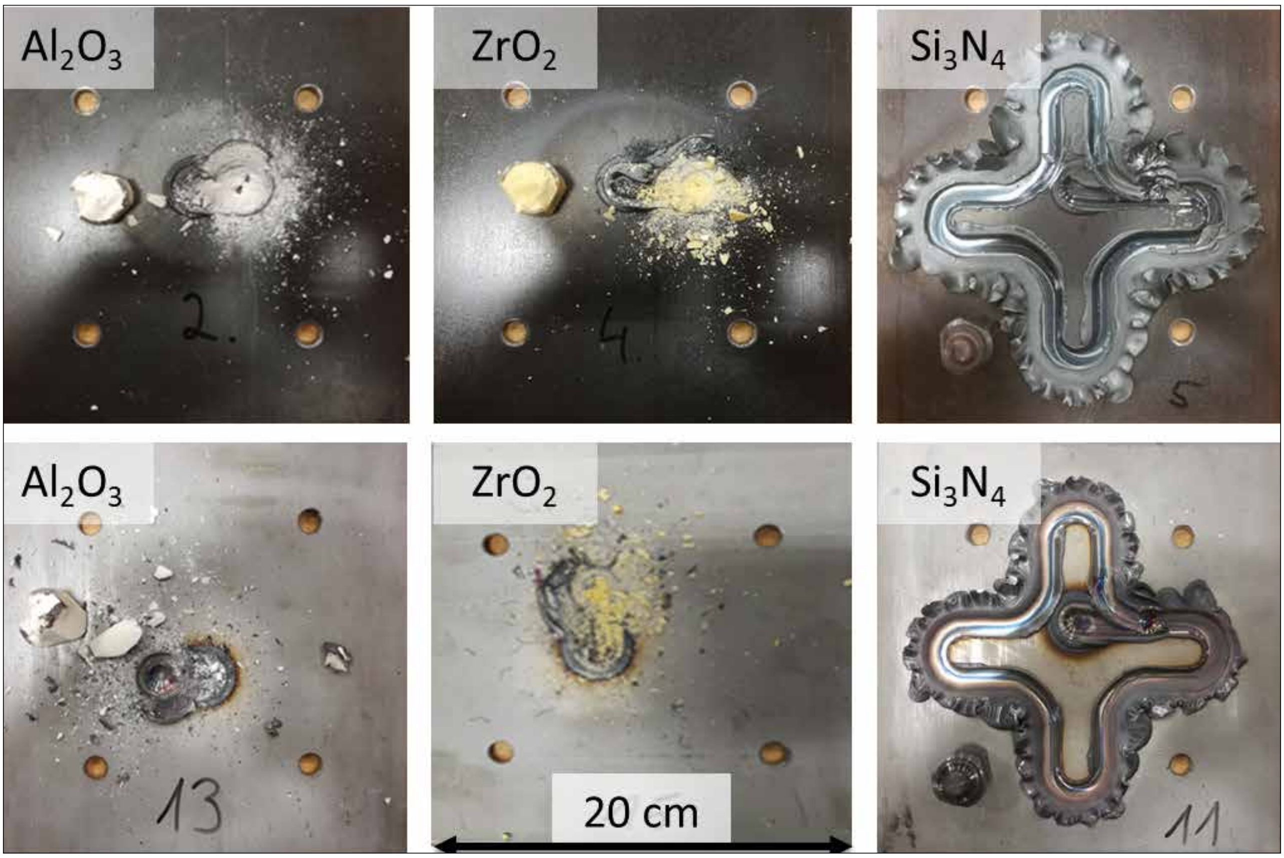

Fig. 6
Results of the tests of oxide as well as non-oxide tools in combination with steel S235JR (top row) or X5CrNi18-10 (bottom row) under realistic conditions

Fig. 7
Experimental setup for wear resistance determination (l.), Si_3N_4-tool before and after 12 immersions, and 9,5 m welding length (r.)

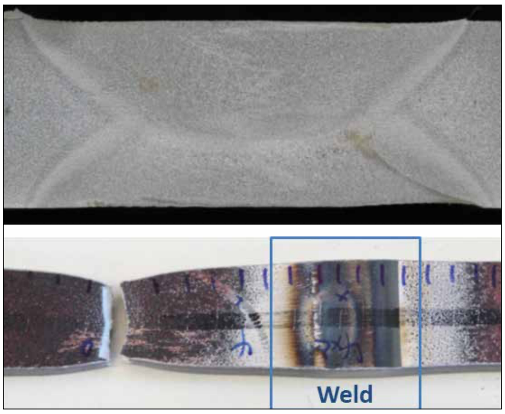

Fig. 8
Steel sheets (S235JR) after welding on both sides (top), and after determination of the tensile strength (bottom)

Fig. 9
First produced FSW tool made of WC–ZrO_2

A test route length of 600 mm was chosen.
Interestingly, the experiments under real conditions show exactly the opposite behaviour compared to the previous results, as can be seen in Fig. 6. Irrespective of the used steel grade, both the alumina as well as the zirconia tools were completely destroyed after applying the feed motion. This was preceded by a clearly audible cracking noise immediately after the shoulder, which corresponds to the largest diameter of the tool, hit the steel sheet. The tools were tested in the cold state and begin to glow red only after a few seconds after immersion, which leads to a thermal shock of the ceramic material. In case of the Si_3N_4-tools, however, no noise could be observed.
As a matter of fact, the entire test route could be driven off, without the formation of defects in the tool. Taking Tab. 1 into consideration, it becomes clear that Si_3N_4 has significantly better thermal shock resistance, and is therefore able to withstand the harsh conditions during welding.
In order to evaluate the wear and thus the long-term stability, a Si_3N_4-tool was immersed into a S235JR sheet with a thickness of 6 mm for 12 times and a welding length of 9,5 m was generated. The tool was still intact even after these stresses, even though significant wear is recognizable, as depicted in Fig. 7. The most pronounced wear is detectable in the cross-section of the pin, which is to be traceable back to the feed motion as well as the convection of the steel.
After confirming the suitability of Si_3N_4 as material for friction stir welding, its influence on the mechanical properties of the weld had to be checked. Therefore, steel sheets (S235JR) with a thickness of 8 mm had been welded on both sides with a Si_3N_4-tool and the following parameters; contact force: 25 kN, number of revolutions: 475 rpm, and a feed motion of approx. 3 mm/min. As evident from Fig. 8, the fracture-causing defect and hence, the failure of the tensile test is located in the base material. As a logical consequence, the determined tensile strength equates to that of steel S235JR. This shows that despite any contamination by the FSW-tool material, no negative influence on the mechanical properties of the join parts is observed.
In order to generate tools with improved wear resistance and taking into account the previous results, the composite WC–ZrO_2 was chosen. This is due to the fact that ZrO_2 has proven itself in preliminary tests, with the exception of thermal shock resistance. WC, however, has good thermal conductivity (60–80 W/m · K) and lower CTE (about $5 \cdot 10^{-6}$ K^{-1}), and thus improves thermal shock resistance.
Moreover, the use of WC can result in the improvement of wear resistance, due to its high hardness, and enables the component to be inductively heated. The material based on 60 vol.-% ZrO_2 and 40 vol.-% WC was initially ground using an agitator bead mill. Subsequently, drying optimisations were carried out by means of freeze dryers and drying chambers.
The optimum pressing conditions were determined by creating a compression pressure curve. By varying the sintering conditions, it has finally been possible to generate a nearly dense component. For this purpose, the cold isostatically pressed green bodies were sintered at 1550 °C under nitrogen atmosphere for 2 h. The sintered component was finally machined by BCE (Fig. 9).
The determination of the material characteristics for the new composite material shows that it can be considered extremely promising, as shown in Tab. 2. Not only

Tab. 2
Comparison of the failure-relevant material characteristics of the new composite material with those the standard material pcBN

Material property	WC–ZrO_2	pcBN
Fracture toughness [MPa*m$^{1/2}$]	10,4	6
Hardness [MPa]	2285	–
Bending strength [MPa]	1139	800
Poisson number [–]	0,25	0,25
Young's modulus [GPa]	189	400
Thermal expansion coefficient RT-1000 °C [10^{-6} K^{-1}]	7	4,9
Thermal conductivity [W/m · K]	50	100
Thermal shock parameter R2* [W/m]	0,0323	0,0306

does it have better properties compared to the materials tested so far, but even a better performance than the costly pcBN can be expected. Friction stir welding tests have already confirmed its suitability.

Conclusion

In the course of the present work, the problems of limited availability of tools and high prices were supposed to be addressed, which lead to the demand of commonly available ceramic alternatives. In this regard, oxides show good tribological and thermochemical resistance towards steel, in contrast to non-oxides. However, tests under realistic conditions have shown that the thermal shock resistance as well as the fracture toughness of the tool materials is of great importance. Here, on the one hand, the Si_3N_4 possesses the best stability.

On the other hand, the wear resistance is still in need of improvement, even though possible contaminations resulting from tool abrasion do not affect the mechanical properties of the weld negatively. Therefore, a new composite tool ($WC–ZrO_2$) with outstanding properties has been developed, and can be consequently classified as very promising.

Acknowledgement

The IGF project “Einsatz des Rührreibschweißens für das Fügen von Stählen unterschiedlicher Güte in Verbindung mit einer gleichzeitigen Entwicklung entsprechender neuartiger keramischer Werkzeuge”, P 1136/06/2017/IGF-Nr. 19213 N of the Forschungsvereinigung Stahlanwendung e.V. (FOSTA), was funded by the AiF as part of the program for the promotion of industrial community research (IGF) by the Federal Ministry for Economic Affairs and Energy. The authors would like to sincerely thank for the experienced financial support.

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