

REVIEW ON THE POSSIBLE TOOL MATERIALS FOR FRICTION STIR WELDING OF STEEL PLATES

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Abstract: The friction stir welding (FSW) process is mainly used in industrial applications for joining low melting temperature materials such as aluminium and magnesium. FSW has many advantages in comparison with conventional fusion arc welding. Therefore the interest to use this technique for joining steel plates has grown. However such usage is still limited because of the lack of adequate tool materials. This review gives an overview of possible tool materials for FSW of steels focussing on tungsten, tungsten carbide, pcBN and a few ultra-high temperature ceramics.

Keywords: FSW, tool material, steel plates

1 INTRODUCTION

Friction stir welding has in comparison with conventional fusion arc welding many metallurgical, environmental and energetic advantages [1]. There are also less process parameters to control which facilitates its use. This solid state joining process is implemented in industrial applications for materials with low melting temperatures such as aluminium and magnesium alloys [2, 3]. However, the development of friction stir welding of steel has progressed more slowly due to the higher temperatures reached and therefore the limited durability of the welding tools.

Previous research has already shown that it is possible to weld mild steel and other low to medium carbon ferrous alloys. Even high carbon steels and stainless steels can be welded successfully with a tungsten-based tool material. The emphasis of this review is to evaluate the feasibility of materials for the production of FSW tools for high strength steels [4-8].

2 TOOL REQUIREMENTS

The tools have to withstand severe conditions during the friction stir welding process. The heat generated during this process, causes high temperatures in the contact zone and also high temperature gradients. According to [9] the work material temperature is possibly increased to about 80% of its melting temperature. For HSLA steels, the temperature can thus reach 1100°C.

To build up resistance against fatigue and fracture, a high fracture toughness of the tool is required. It is also important that the ductile to brittle transition temperature of the tool material is sufficiently low. Indeed, materials that are brittle at room temperature might fail during the initial plunge stage.

It is necessary that the tool's hardness and strength don't decrease much in these high temperature circumstances to ensure that tool deformation and wear are limited.

The thermal conductivity of the tool material is a measure for the rate of heat removal. It affects the temperature field, flow stress and the weld microstructure. A high thermal conductivity avoids the formation of hot spots on the tool and allows the use of a cooling mechanism to lower the temperature of the tool. However, high thermal conductivity causes an excessive removal of heat from the weld region which implies the need of higher welding forces [10].

To obtain a smooth weld surface, a low coefficient of friction between tool material and workpiece is required. From experience it is known that FSW of steel with pcBN results in a smooth welding surface [10].

It is favourable that the tool is chemically inert with respect to ferrous materials and corrosion resistant.

As the tool geometry plays an important role in the formation of the weld [11], it is profitable that the tool material is easy to machine. However to weld high strength steels, hard metals and ceramics are used and these materials are known to be rather difficult to machine.

The main challenge for the industrial exploitation of FSW of steels is undoubtedly the development of a reliable, lasting and cost effective tool material and this is where the potential benefits of research could be large [12].

3 CANDIDATE TOOL MATERIALS

3.1 Tungsten Carbide (WC)

WC is a very strong material due to the covalent bonding between the W and C atoms. This bonding also leads to a high melting temperature of about 2900°C and a high hardness at room temperature up to 27GPa. Tungsten carbide however is brittle in nature with a fracture toughness between 2-4 MPa.m^{1/2}.

To enhance different mechanical properties and sinterability, a second phase material is added. In the following, different second phase materials are discussed, in particular their advantages and disadvantages for use in FSW.

3.1.1 Metallic binder

The addition of **cobalt** leads to an excellent wettability and adhesion with the tungsten carbide. This facilitates sintering and increases strength and toughness considerably. The hardness and wear resistance however are inversely proportional to the added cobalt content. The mechanical properties are strongly dependent on grain grade and added cobalt content as can be seen in Figure 1.

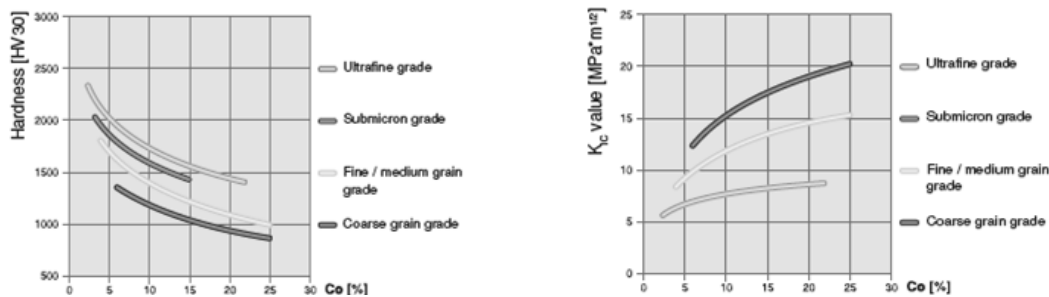


Figure 1: Hardness and fracture toughness of WC-Co with varying Cobalt content [13]

Experiments showed that the metallic binder is inferior to the WC in corrosive and elevated temperature applications [14]. At temperatures above 600°C, a significant strength degradation is observed. This degradation is caused by high oxidation rates and the development of microstructural defects [15].

Figure 2 shows the softening of WC-Co at temperatures above 600°C. Since temperatures up to 1000°C are common during friction stir welding, research is required to find other materials that maintain their properties at these high temperatures.

The advantages of using **nickel** instead of cobalt as binder are the improved corrosion and oxidation resistance [16-20]. WC-Ni is also favorable to use instead of WC-Co in applications where hot hardness and resistance against thermal cracking are essential [16, 17]. However, the difference with WC-Co is not significant. Mechanical properties of WC-Ni with varying nickel content are presented in Figure 3.

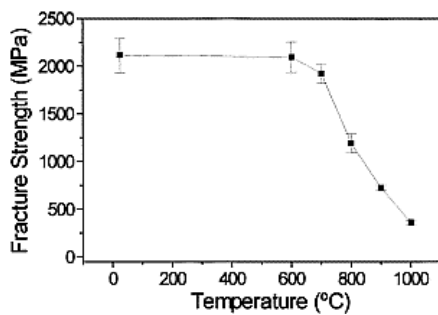


Figure 2. Fracture strength of WC-Co at high temperatures [15, 21]

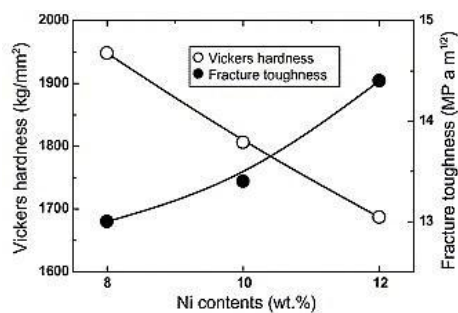


Figure 3. Hardness and fracture toughness of WC-Ni with varying Ni-content [19]

3.1.2 Ceramic binder

The utilization of **zirconia** (ZrO_2) as a ceramic additive instead of a metallic binder is interesting because zirconia is an electrical and thermal isolator and does not soften at elevated temperatures. It is also not susceptible to electrochemical corrosion. The addition of zirconia to WC leads to an increase in fracture toughness due to transformation toughening and a small decrease in Vickers hardness [22].

Adding **alumina** (Al_2O_3) results in a tool material that combines two opposite properties, high hardness and relatively high fracture toughness, which makes it very attractive for the use as cutting or welding tool [36]. Experiments showed that adding alumina has a remarkable influence on microstructure, the crack propagation path and the mechanical properties. With increasing content of Al_2O_3 , the relative density increases while Vickers hardness and fracture toughness initially increase to their maximum values and then decrease [23]. Another study found apparently contrasting results as can be seen in Figure 4. They found that the addition of alumina results in a toughening effect, but the hardness decreases [14]. The difference in both studies indicates that the mechanical properties are not only dependent on alumina content but also on the production process and the properties of the different base materials.

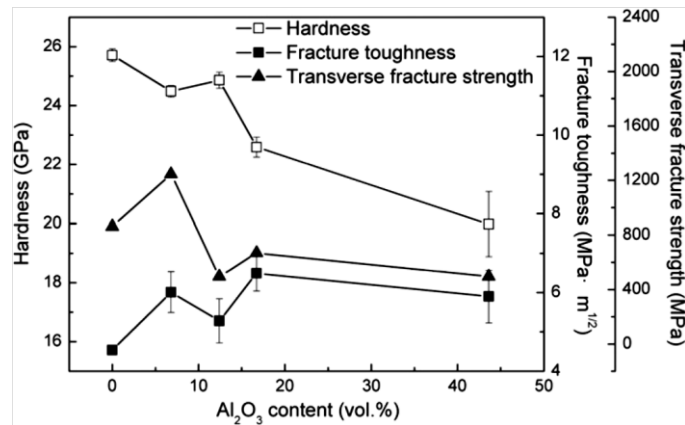


Figure 4. Mechanical properties of WC- Al_2O_3 with varying alumina content [14]

The addition of **titanium diboride** (TiB_2) and some sintering additives to the pure WC leads to an increase in fracture toughness without decreasing the hardness significantly. Titanium diboride has very good mechanical properties. It has a high hardness around 32 GPa and good corrosion and wear resistance [24].

Typical hardness and fracture toughness values of WC for the different ceramic additives are summarized in Table 1.

Table 1. Hardness and fracture toughness of WC with ceramic binder [14, 22, 23, 25]

Ceramic additive	ZrO_2	Al_2O_3	TiB_2
Vickers Hardness [GPa]	18-23	16-25	18-22
Fracture toughness [$MPa \cdot m^{1/2}$]	4.9-6.2	6-10	6-8

3.1.3 Cubic Boron Nitrides

The addition of **cBN particles** to the WC-Co base material leads to a slight increase in hardness, a significant increase in fracture toughness and a moderate decrease of mechanical strength. The hardness increases due to the high hardness of the cBN particles. An increase in fracture toughness can be obtained due to the crack deflection effect of the cBN particles [26, 27].

The addition of cBN particles to the cemented carbides significantly decreases the sinterability. Therefore these composites are usually sintered by very costly techniques applying high temperatures and ultra-high pressures (>5-8GPa). The difficulty is the low stability of the high hardness cBN particles at high temperatures [26, 27].

Hardness and fracture toughness of WC-cBN are shown in Table 2.

Table 2. Hardness and fracture toughness of WC-cBN [26]

Co content (wt%)	cBN content (vol%)	HV [GPa]	K_{Ic} [MPa.m ^{1/2}]
1	30 (A)	25.00	10.5
	30 (B)	25.00	-
5	50 (A)	22.30	15.3
	50 (B)	21.50	15.4
	50 (C)	21.50	14.7
7	50 (A)	22.30	No cracks
10	50 (A)	21.10	No cracks

The letters (A-C) represent different cBN powder grades where C represents the finest grade.

3.2 Tungsten Rhenium (W-Re)

The addition of rhenium to tungsten is very effective to lower the ductile to brittle transition temperature [28], which is defined as the temperature for 5% elongation. This temperature is 350K when 25%Re is added and is considerably lower than the other alloys. It is even possible to obtain a ductile to brittle transition temperature of -50°C [10].

As can be seen in Figure 5, alloying tungsten with rhenium not only affects this transition temperature but also the ductility above the transition temperature. The ductility decreases with increasing rhenium content above 600K, the slope of the ductility-temperature curve also decreases.

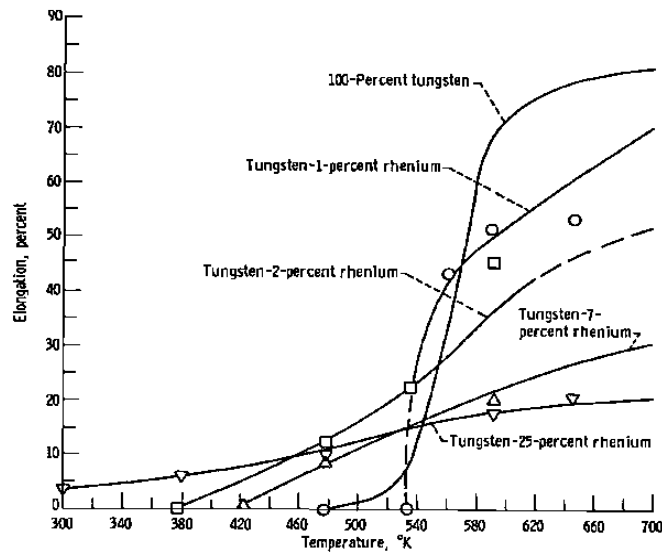


Figure 5. Effect of rhenium on ductility of arc-melted tungsten [28].

The yield strength and tensile strength are represented in Figure 6 as a function of temperature and rhenium content. The yield and ultimate tensile strength decreases with increasing temperature. By adding the component HfC, a clear improvement of the strength is obtained.

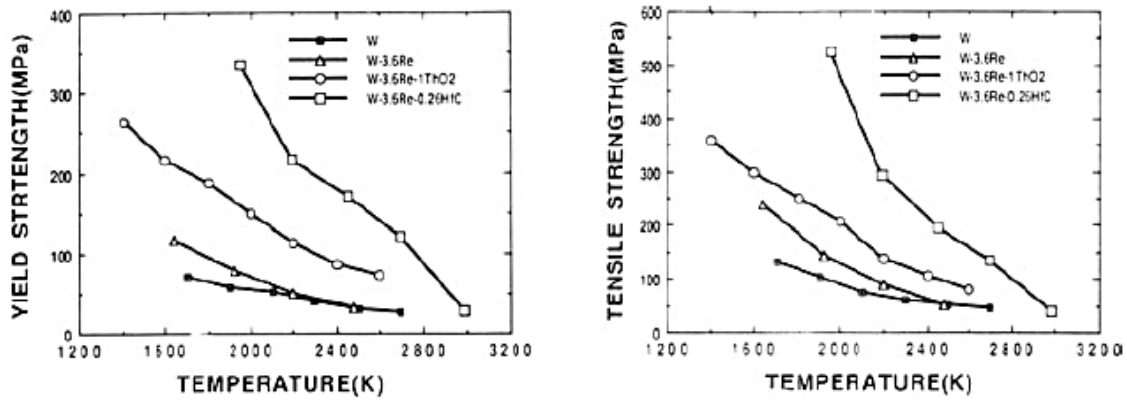


Figure 6. Yield strength and ultimate tensile strength of Tungsten Rhenium alloys as a function of temperature [29]

3.3 Polycrystalline cubic boron nitride (pcBN)

pcBN is a composite material consisting of small cBN particles bonded together in a skeletal matrix. cBN is the second hardest material after diamond which results in a very high hardness of pcBN (>30GPa) [30].

As tool material, pcBN has to maintain this high hardness at high temperature. In Figure 7 the variation of hardness is plotted as a function of cBN content and temperature. There is an increase in hardness with cBN content. However in the temperature range 600-1000°C the rate of change of hardness is not significant. As expected, the hardness decreases with increasing temperature but the hardness at 1000°C is still higher than for many materials.

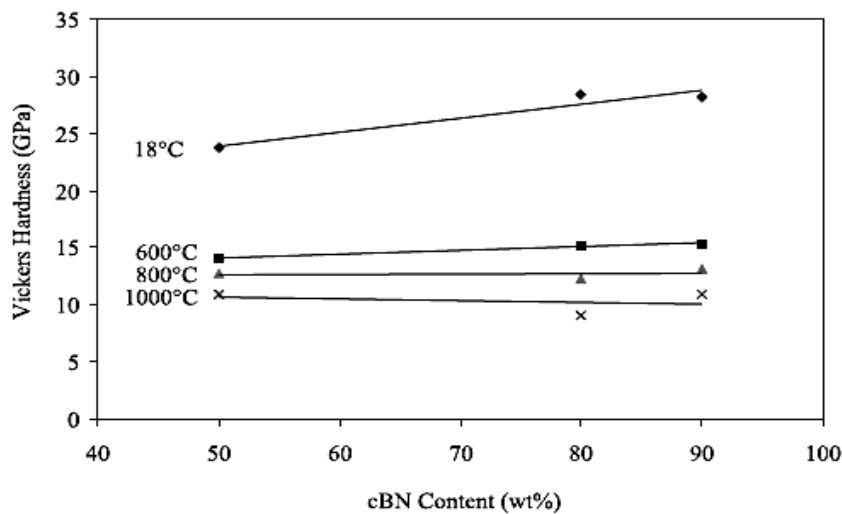


Figure 7. Variation in hardness with cBN content and temperature [31]

Another advantage of pcBN when used for the friction stir welding of steel is its low coefficient of friction which results in a smooth welding surface.

In general pcBN is used due to its very high hardness, wear resistance and thermal stability. It is inert to ferrous materials at temperatures above 1000°C while maintaining its strength [30]. On the other hand, pcBN is very expensive to manufacture and has a relatively low fracture toughness ($4-6 \text{ MPa}\cdot\text{m}^{1/2}$), therefore pcBN has the tendency to fail during the initial plunge stage [32]. Generally, when higher fracture toughness is required, tools with high pcBN content (80-90%) and a metallic binder are used. Tools with low pcBN content (45-65%) and a ceramic binder are more resistant to diffusion wear [33].

3.4 Ultrahigh temperature ceramics

Transition metal diborides (TiB_2 , ZrB_2 , HfB_2 , etc.) are commonly known as ultra-high temperature ceramics (UHTCs) as they possess melting temperatures above 3000°C.

3.4.1 Zirconium diboride (ZrB_2)

The use of ZrB_2 is still limited because of its very low fracture toughness and strength. To improve the mechanical properties, ceramic additives or a second phase with strengthening and toughening capabilities can be added. Another disadvantage of ZrB_2 is the oxidation in air at elevated temperatures. It has been shown that the oxidation resistance of ZrB_2 can be further enhanced by reacting it with up to 15% SiC [34].

A comparison of the mechanical properties of ZrB_2 as a function of SiC content is presented in Table 3. The specimens tested were sintered for 3 hours at a temperature of 2000°C. There is also 5% carbon added based on SiC weight and 4% B_4C based on ZrB_2 weight.

Table 3. Comparison of mechanical properties of ZrB_2 with 10, 20 and 30 vol% SiC [35]

SiC volume fraction [vol%]	Elastic Modulus [GPa]	Hardness [GPa]	Flexure strength [MPa]	Toughness [$MPa \cdot m^{1/2}$]
10	446 ± 7	15.3 ± 1.2	404 ± 62	3.1 ± 0.1
20	474 ± 7	18.8 ± 1.1	463 ± 53	3.4 ± 0.1
30	490 ± 7	22.4 ± 0.7	492 ± 49	3.5 ± 0.3

The thermal conductivity of ZrB_2 lies between $60-140 \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$ and unlike most ceramics ZrB_2 has a good electrical conductivity and complex shaped parts can easily be made by electrical discharge machining [35, 36].

3.4.2 Transition metal diborides (TiB_2) and boron carbide (B_4C)

Looking at the mechanical and physical properties, TiB_2 can be very attractive for friction stir welding applications. The hardness at room temperature varies between 2500 – 2700 HV and the fracture toughness between 6 – 8 $MPa \cdot m^{1/2}$. However, according to [37], TiB_2 is difficult to sinter because of its covalent bonding nature, low self-diffusion coefficient and presence of an oxide layer (TiO_2 and B_2O_3) on the TiB_2 powder surface. The use of metallic or non-metallic sinter additives is essential to enhance the sinterability of TiB_2 . However, the mechanical properties will also be affected with the additives [37].

Boron carbide (B_4C) ceramics possess a very a high hardness (38-42 GPa) and a high melting point (2370-2480°C). It is a promising candidate for wear resistant components. However, the use of B_4C is restricted because of a low fracture toughness ($<2.2 \text{ MPa} \cdot \text{m}^{1/2}$) and poor sinterability [38].

To improve the fracture toughness of B_4C , TiB_2-B_4C is formed. Since TiB_2 and B_4C have high hardness and high melting points, the composite can be used for advanced structural materials [38]. In Figure 8 the influence of the amount of TiB_2 on fracture toughness is shown.

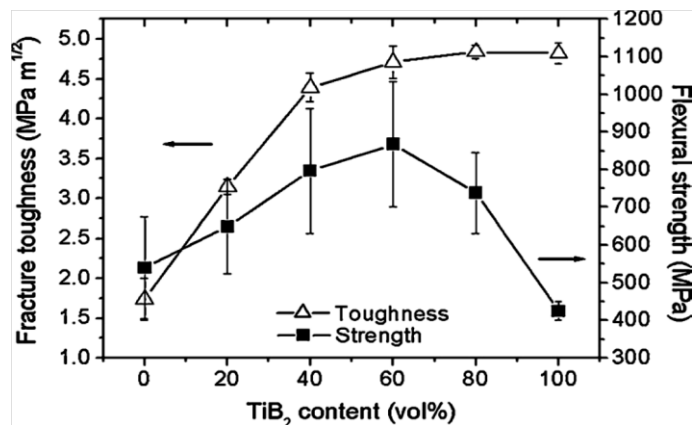


Figure 8. Influence of the amount of TiB_2 on fracture toughness and flexural strength of TiB_2-B_4C [39]

4 CONCLUSION

The interest in the development of FSW of steel has grown the last decade. In comparison with FSW of low melting temperature materials, the requirements of the tools are more severe. Tungsten, tungsten carbide, pcBN and ultra-high temperature ceramics are candidate tool materials. Their properties, advantages and

drawbacks have been discussed. Mechanical properties such as hardness and fracture toughness at ambient temperature are summarized in Table 4. The behaviour of these materials at high temperatures however still needs a lot of investigation.

Table 4. Mechanical properties of the discussed materials at ambient temperature

Material	Additive	Hardness [GPa]	Fracture toughness [MPa.m ^{1/2}]	At high temperature?
WC	Co	10-20	5-20	Softening at temperatures above 600°C
	Ni	15-20	10-15	Similar behaviour as with Co
	ZrO ₂	18-23	4.5-6.5	Unknown but ceramic binder is expected to behave better at high temperatures than a metallic one.
	Al ₂ O ₃	16-25	6-10	
	TiB ₂	18-22	6-8	
	cBN	20-25	10-15	cBN high temperature resistant
W-Re	-	7		unknown
pcBN	-	23-27	4-6	Remains required hardness and strength
ZrB ₂		15-23	3-4	Ultra high temperature ceramic
TiB ₂		25-27	6-8	

During this research, a test setup will be developed to simulate the tool conditions that appear during the FSW process. Different materials will be tested and their performance will be evaluated.

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