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Technical Paper

Characterization of WC/12Co cermet–steel dissimilar friction stir welds

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ABSTRACT

The present work is original since for the first time it deals with the lap friction stir welding of a steel to a cermet. A Si_3N_4 sintered tool was used. The paper more particularly focuses on the effect of the load exerted on the tool inserted in steel on (1) the tool wear and contamination, (2) the joint interface features and (3) the steel microstructure. The phase transformations in the different weld zones of the steel are explained by the thermal cycles. The hardness and shear lap tensile properties of the different joints are finally correlated to their microstructure.

1. Introduction

Novel applications with ever more demanding specifications require the combination of performing materials of different natures, which raises the challenge of their assembly.

Joining ceramic to alloys presents the interest of combining the hardness and abrasion and thermal resistance of cermet, to the toughness and ductility of metals. Various processes among which

- brazing with distinct convection flows because of different heating sources like electric resistance furnace, induction heating and oxyacetylene welding [1–9],
- welding processes such as gas tungsten arc welding (GTAW) [10], tungsten inert gas (TIG) welding [11], laser welding [12,13], fiber laser welding [14], electron beam welding [15], oxyacetylene welding [7], diffusion welding [16–19] or plasma activated sintering giving rise to diffusion welding [20],
- hybrid processes associating either brazing and TIG welding with direct current negative mode electrode [21], or laser and TIG welding [22] or even high velocity oxygen fuel thermal spraying combined with friction stir processing [23]

were reported to join cemented carbide and steel.

However, the peculiar topic concerned by ceramic based composite – metal joining raises various issues because of the different nature of chemical bonds for both materials, which is ionic and covalent in ceramics and metallic in alloys. Indeed the mechanical resistance of the joint will depend on at least the wettability of the ceramic by the metal, the difference of coefficients of thermal expansion of both kinds of materials, and the eventual formation of brittle phases at the joint interface.

The wettability of the ceramic by the metallic constituent will directly govern the interface features and the bonding quality in the cases of brazing and liquid state welding. The wettability directly depends on the atmosphere, on the temperature, on the chemical affinity between both components and on solid surface features such as roughness, lattice mismatch and crystallographic misorientation [24–27]. For the case of ceramic with an ionic oxygen character, the wettability can be improved by applying a direct current voltage at the liquid metal – ceramic interface. This electrical current induces phase transformations at the interface contributing to a significant increase of the strength of the joint which is multiplied by 8 [25]. Another way to enhance the wettability is to use an active filler metal with a judicious chemical composition [27] such as

1) an Ag based alloy containing Co and Ni which improves the wettability by a graded distribution of Co and Ag across the interface.

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The addition of Co in the braze compensates for the extension of the Co-depleted zone in the cemented carbide while Ni gives rise to diffusion bonding with the steel. A Co-depleted zone in the cermet indeed decreases the joint strength [28],

2) a Cu-Zn-10Ni filler metal which entails diffusion of Ni towards steel and of the Co contained in the cement into the braze [7] while limiting the extent of the Co depleted zone,
3) a 70Cu-30Zn filler metal which leads to the formation of a (Cu,Ni) solid solution along the Ni coated cermet and of a Fe and Cr rich Cu solid solution along the steel. Both solid solutions favor the intimate bonding, while Zn enhances the wettability of the cermet before being evaporated during brazing under vacuum [5], and
4) a Ag-Cu filler which gives rise to interdiffusion on each side of the filler [3].

As previously referred to, coating layers may also favor wetting. Coating of ceramic with an active metal [24,26] such as Ni on WC/Co [4], coating of the steel with 70Ni-30Cu [16] or even the electrolytical coating of a Cu-Zn braze interlayer with Ni [4] are convincing examples.

The distinct coefficients of thermal expansion (CTE) of the cermet and of the metallic alloy will generate some residual stresses at the interface. Various ways were used to relieve the stress concentration at the interface such as:

– a Ni coating on WC/Co cermet by powder metallurgy [4,19] which presents an excellent plasticity and absorbs the stresses generated in the braze [5], or a Cu/Ni coating electroplated on steel to promote interdiffusion with both metals which leads to solid solutions relaxing internal stresses [17],
– the addition of

○ an interlayer of either Ni [18,20], Ni-Cu [18] or Ni-Cr in an Ag based filler metal [21],
○ several interlayers such as a bilayer of Cu alloy-amorphous Ni alloy together with oil cooling after brazing [1,8],
○ a graded composite [5,24,26].

– a filler metal like a Ag + Ni + Co alloy since Ag presents a low melting temperature and a good chemical affinity for WC, and Ni and Co additions prevent the formation of a Co depleted zone [1,6],
– a composite braze containing either ceramic particles or fibers [26], or a metallic foam [29] which gets a graded CTE composite between the base materials in the first case and improves the strength of the braze in the second case,
– an increase of the proportion of steel in the cermet-steel joint [18].
– a post heat treatment after either laser welding [12] or electron beam welding [15],
– the application of a compaction pressure (60 MPa) on the joint during its cooling [30].

At last, the formation of the Fe_3W_3C and/or Co_3W_3C, Co_2W_4C, Co_4W_2C η brittle phases at the interface can entail poor mechanical resistance of the joints and in particular low shear strength [4,9,12,14,15]. The latter reactions are all the more favored that joining proceeds at the liquid, or at the solid state for a long time as in diffusion welding. Various solutions were proposed to limit the formation of the ternary carbides. The nitriding of the cermet has enabled to reduce the amount of brittle carbides at a joint get by laser welding [12]. Besides, an addition of Cr_3C_2 in the cemented carbide prevents both the formation of Co_3W_3C (η) and the coarsening of the WC grains in diffusion welding. This addition must however remain below 1 wt.% so as to not deteriorate the joint shear strength because of the formation of Cr_7C_3 at the interface [8]. The use of a Ni-Fe-C filler metal has also been shown to inhibit the η phase formation during TIG welding [11].

According to Table 1, the shear strength of the steel/cermet joints generally remains lower than 400 MPa irrespective of the joining process except either laser welding with an Invar interlayer [14] or diffusion welding with a Cu/Ni bilayer [17].

The current study focuses on joining medium carbon steel and WC/12Co cermet. Such joints present an interest for the machining field where various applications dealing with cutting tools and

Table 1
Chemical compositions, –joining processes and set up, and shear strengths of cemented carbide – steel joints.

Process	Steel	Cemented carbide	Coating (C)/Interlayer (I) (thickness)	Maximum shear strength (MPa)	Reference
Brazing	Stainless steel 410 (AISI 410)	WC-8%Co	Ni (C) on cermet (0.5 mm) + 70Cu-30Zn (I) (0.2 mm)	260	[5]
	Carbon tool steel (0.45 wt.C)	WC-8% Co with 0.5% Cr_2O_3	Cu (100 μm)/Ni (40 μm) (I), Cu on steel and Ni on cermet	370	[8]
	3Cr13 stainless steel (Fe-0.325%C-13.430%Cr-0.025%Mn-0.390%Si-0.020%S-0.080%Ni (wt))	WC-8% Co	Cu-Zn (0.2 mm) (I) with Ni electroplated on each part of the interlayer	154	[4]
	SAE 1045 steel	WC-Co	Cu or bronze (I)	320	[2]
High frequency induction brazing	(35CrMo steel Fe-0.35%C-1%Cr-0.2%Mo-0.2%Si-0.5%Mn (wt))	WC-20%Co	Ag-16%Cu-23%Zn-7.5%Mn –4.5%Ni (I) (120 μm)	366	[9]
TIG brazing	AISI 1020 steel (0.21%C)	WC-10%Co	Ni (C) on cermet + Ag based (I) + NiCr (I) (?)	289	[21]
Laser welding	AISI 1045 steel	WC-20%Co	Fe-42%Ni Invar (I) (?)	981 (maximum bending strength)	[14]
Electron beam welding	AISI 1045	WC-Co	Ni90-Fe8.2-C0.5-Y0.8-Nb0.5 (I) (1 mm)	–	[15]
Diffusion welding	90MnCrV8 steel (AISI 01)	WC-15%Co	Cu (10 μm)/Ni(10 μm) (C on steel)	600	[17]
	Stainless steel 410 (AISI 410)	WC-8%Co	Ni (C on cermet) (?)	260	[19]
	90MnCrV8 steel (Fe-0.910%C-1.980%Mn-0.170%Si-0.015%P-0.009%S-0.430%Cr-0.080%V (wt))	WC-Co	70Ni-30Cu (C on steel) (20 μm)	136	[16]
	Steel (0.45 wt.% C)	WC-24%Co	Ni or FeNi14 or NiCu (I) (0.1 mm)	360	[18]
	AISI 410 stainless steel	WC-8%Co	Ni (C)	195	[19]
Plasma activated sintering	40Cr steel (Fe-0.43%C-0.22%Si-0.57%Mn-0.96%Cr-$<$0.035%S-$<$0.035%P (wt))	WC-10%Co	Ni (I) (50 μm)	293	[20]