Interfacial evolution of WC-Co/AISI 304L diffusion bonded joint obtained by flash SPS technique

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Abstract: - In this work, WC-Co cermet was successfully joined to AISI 304L stainless steel using flash spark plasma sintering (FSPS) technique under a constant load of 5 MPa with ultra-rapid holding times. The results revealed that increasing the holding time to 12s resulted in massive interfacial deformations accompanied with an important diffusion activity of Co, Ni and Fe across the interface. Toughness measurement of WC-Co cermet at the vicinity of the bonding interface was assessed using Vickers indentation fracture (VIF) method. The results revealed that the mechanical properties of the bonded joints deteriorated with increasing holding time, leading to increased brittleness. This outcome was observed despite the significant inter-diffusion that occurred between the WC-Co cermet and the constituents of the 304L steel

Key-Words: - WC-Co cermet, inter-diffusion, Flash SPS, Microstructure, Interface, Fracture toughness.

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1 Introduction

In the last decades, the challenge of the WC-Co cermet/steel joining raises much interest, in order to perform a material with highly distinguished properties [1,2]. Due to the great difference in their physical properties and their chemical nature, joining WC-Co cermet to steel using conventional welding methods is so difficult [3,4]. Therefore, an important research works has been performed to achieve an acceptable dissimilar joint, with high strength using various advanced techniques such as: diffusion bonding [5,6], laser welding [7], friction welding [1,2] and hybrid and TIG welding [8,9]. In the dissimilar joining, the key to obtain a high quality joint, is to avoid the formation of brittle phases and/or intermetallic at the weld interface which can cause the premature failure of the weld joint. Many research studies have shown that the WC-Co/steel interface is the weakest area of the join where the fracture occurs frequently. As reported by Ma et al. [10] in WC-Co/invar laser weld joint, the cracks initiate at the interface and propagate through the WC facet, which makes the WC-Co at the vicinity of the interface susceptible to cracking. This behavior is attributed to several factors, among them, the

mismatch between the steel and the WC-Co cermet thermal properties during cooling process. Most often, the thermal expansion coefficient of the steel is larger than that of the WC-Co cermet [11,12]. Consequently, detrimental residual stresses are generated along the joint interface especially in the WC-Co cermet can be expected, and their level depend on one hand, how close they are to the interface and, on the other hand, the joining parameters and/or conditions.

In this work, WC-Co cermet has successfully been welded to AISI 304L stainless steel using rapid diffusion bonding process. The weld joints have been performed using flash SPS machine with different holding times (4s to 12s) at 5MPa constant load. We aim to investigate through this work, the interdependence between the manufacturing conditions (holding time), residual stress and the microstructure features of WC-Co/steel joints issued from different times.

2 II. Materials and experimental procedures

In this work, WC-10%Co was joined to AISI 304L austenitic stainless steel (8 wt. % Ni and 18 wt.% Cr) with cylindrical shape of 5mm of length and 8mm of diameter. The dissimilar assembly was obtained by using flash spark plasma sintering (FSPS) machine as illustrated in Fig. 1. The WC-Co cermet was placed onto the AISI 304L steel, put into a graphite die and inserted in the FSPS machine under a constant load of 5 MPa. The bonding operation was carried out at different times (4s, 6s, 8s, 10s and 12s) under shielded atmosphere of argon using DC mode. The cooling process was conducted in the FSPS machine and the cooling rate was about (100°C/s). A Zeiss optical microscope and a Zeiss AURIGA scanning electron microscope with an energy dispersive spectroscope (EDS) were utilized for microstructural examination and semi-quantitative chemical analyses.

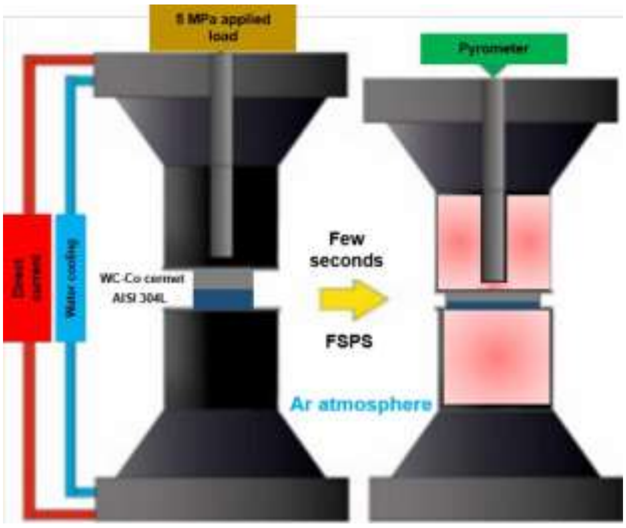

Fig. 1: Schematic illustration of the flash SPS bonding process.

3 Results and discussion

Fig. 2(a-d) illustrates the optical macrographs of the samples joined by FSPS using different holding times. The weld joints exhibit a good bending where the line interface can easily be distinguished. As expected, increasing the holding time results in important plastic deformation of the AISI 304 steel pointed by the red dashed lines in Fig. 2(b-d). For 4s to 8s weld joint, no micro-defect can be observed along the weld interface, however, in 10s weld joint, remarkable cracks are identified at WC-Co/AISI 304L steel interface (Fig. 2d).

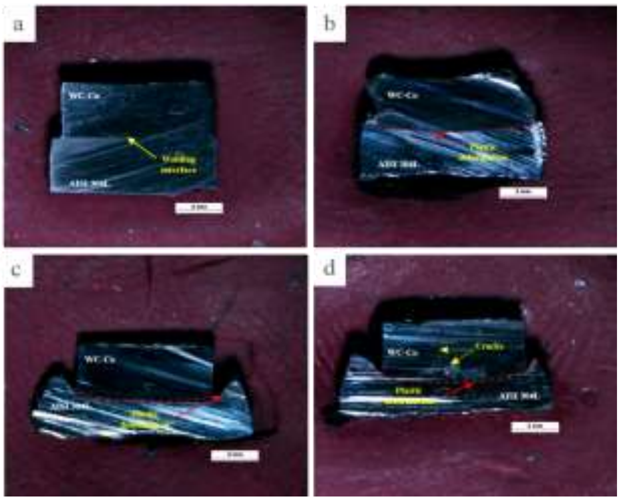

Fig. 2: Macrographic images of the FSPS weld joints obtained using different holding times: (a):4s, (b): 6s, (c): 8s and (d): 10s.

The effect of holding time with respect to the quality of the weld joint can be appreciated in Fig. 3(a-b). At low holding time (4s), the WC-Co cermet/AISI 304L steel interface has a linear aspect which can be attributed to the low diffusion of elements across the weld interface. As observed in Fig. 3a, with increasing the holding time to 6s, the Fe and Ni elements diffuse into the cermet and vice versa. Another point should be noted is the significant dissolution of W and Co at the interface and the substitution of this latest with Ni due to the high mutual solubility between the W and Ni compared to that with Co [13] as shown in region 1 (Fig. 3a). The weld joint obtained using 10s presents an important plastic deformation of the steel with high concentration of cracks in the WC-Co cermet along the line interface. This behavior results in a consistent inter-diffusion of the cermet and the steel constituents and enhances the metallurgical bending of the joint. However, due to the low thermal conductivity of the WC-Co compared to the steel one, high stresses are generated at the interface which induce cracks appearance in the WC-Co cermet along the interface (region 2 and 3). In order to better understand the inter-diffusion and elements activity occurred at the WC-Co/AISI304 steel interface,
EDS profile and point analyses were conducted as shown in Fig. 4(a-b). EDS analysis approve that the Ni and Fe elements dissolve into the WC-Co cermet and the WC particles undergo high plastic

deformation and form with the steel elements a new component rich in W, Ni and Fe (see Fig. 4a and 4b).

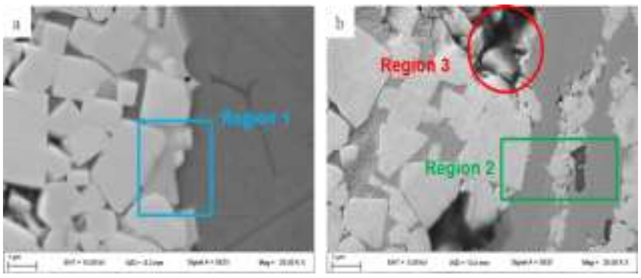

Fig. 3: SEM micrographs of the WC-Co/AISI 304 L interfaces for (a): 6s and (b): 10s holding time

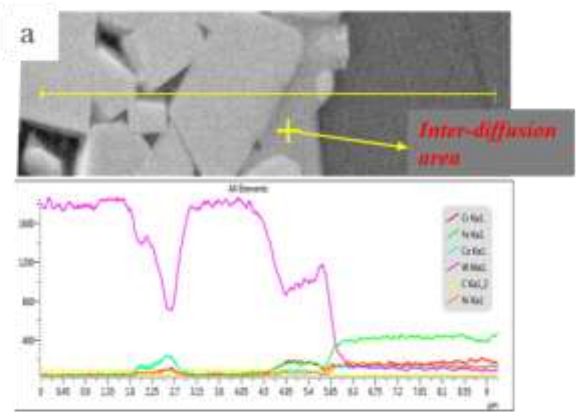

Fig. 4: EDS analysis conducted in region 1 highlighted in Fig. 3a, (a): EDS SEM micrograph of the interface. (b): EDS profile analysis,

The effect of holding time on the fracture toughness (K_{IC}) of the WC-Co cermet/AISI 304L steel joints calculated at the vicinity of the weld interface using Shetty formula (1) [14] is illustrated in Fig. 5

$$K_{IC} = 0.0028\sqrt{H}\,\frac{P}{\sum L} \qquad (1)$$

Where H is the hardness (N/mm2), P is the applied load (N) and ΣL is the sum of crack lengths (mm).

It is observed that the VIF toughness decreases with holding time and achieves 14.8 MPa.m-1/2 for 10s. This behavior of WC-Co cermet is strongly related to the compression stresses induced from the plastic deformation of the materials during FSPS welding process and that increase with holding time. Hence, increasing the bonding time results in the brittleness of the WC-Co cermet which can causes the premature failure of the weld joint. Besides, these cracks start from the corners of the indents and develop and propagate much more in the parallel direction to the line interface than the perpendicular one which is more likely due to the difference in thermal expansion between the different zones in WC-Co cermet.

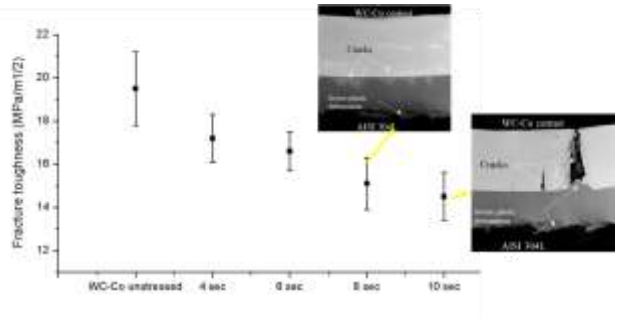

Fig. 5: Variation of fracture toughness (K_{IC}) as function of holding time

4 Conclusion

The key issues of this work are summarized as follows:

- Flash SPS process is believed to be an effective technique to perform an acceptable WC-Co/steel joints with an appropriate holding time considering the other parameters.
- At the joint interface, the inter-diffusion of Ni, Fe and W elements is activated by the plastic deformation which became more prominent with holding time.
- Increasing the bonding time results in the brittleness of the WC-Co cermet which can causes the premature failure of the weld joint.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Bille Cheniti: designed and conducted the experiments, analyzed the data, and wrote the manuscript
Brahim Belkessa and Bouzid Maamache : performed data analysis, and provided critical revisions to the manuscript
Naima Ouali: contributed to the data collection and analysi
Viktor Puchy has organized and executed the FSPS experiments
Pavol hvizdos, supervised the project, provided guidance throughout the research, and reviewed the manuscript

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Conflict of Interest
The authors have no conflicts of interest to declare that are relevant to the content of this article.