

Article

Fast Joining of the 40Cr/WC-8Co Combination with Ag28Cu Interlayer Through the Spark Plasma Sintering Process

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Abstract

The solid joining between the WC-8Co cemented carbide and alloy steels has great significance for their extensive applications. In this study, the WC-8Co and 40Cr steel were joined with the Ag-28Cu interlayer through the SPS method. The microstructure and mechanical properties of the joints obtained at three temperatures—740 °C, 760 °C, and 780 °C—were analyzed. The joining mechanism was studied, and the relationship between the microstructure and shear strength of the joints was also revealed. When processed at 740 °C, the poor bonding between the interlayer and the 40Cr substrates damaged the joint strength. Higher bonding temperature helped to eliminate the interfacial defects. The joint bonded at 760 °C consists mainly of Ag, Cu within the interlayer and Co-rich Fe(s,s) at the substrate/interlayer interfaces, without any defects. In such a case, the shear strength of the joints reached the maximum level of 236 MPa. However, the increased residual stresses at higher bonding temperatures (780 °C) spoiled the strength of the joints, resulting in the decreasing of the shear strength to 173 MPa. The study shed light on the fast joining of the WC-Co and alloy steels at relatively low temperatures.

Keywords: WC-8Co; spark plasma sintering; cemented carbide; microstructure; mechanical property



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1. Introduction

The WC-Co hard metals were widely used in the geological exploration, petroleum extraction, aerospace, and construction engineering fields [1–3], owing to their outstanding hardness, fracture strength, excellent wear resistance, and corrosion resistance [4,5]. In these cemented carbides, the WC-8Co was the most studied, which played an indispensable role in the modern industry [6]. However, the high brittleness as well as the large density of the WC-8Co cemented carbides greatly elevated the cost for its deformation process and hampered its more extensive application in the large or complex structural components [7,8]. Therefore, the WC-8Co material was usually combined with the traditional alloy steels [9,10], such as the 40Cr. The steels exhibit excellent mechanical strength, superior ductility, and, most importantly, much lower processing cost [11–13]. The solid joining of WC-Co/40Cr joints combined the advantages of both materials, thus improving their application stability in harsh working conditions.

Nowadays, the welding methods, such as arc welding and laser welding [14–16], and the solid joining process, such as brazing and diffusion bonding [17–19], have been utilized

to join the WC-Co and alloy steels. In the direct welding process, a large thermal input would damage the mechanical properties of the substrates [12]. Moreover, the notorious residual stresses generated by the large coefficient of thermal expansion (CTE) discrepancy between the WC-Co and alloy steels would greatly reduce the strength of the joints [20]. In comparison, the solid joining method gradually became more accepted due to its lower processing temperature. In recent years, the SPS technique has been widely utilized in joining dissimilar materials due to its convenient operation, lower joining temperature, and fast joining process [21,22]. During the SPS joining process, a dissimilar combination can be achieved under the collaborative electric heating and pressure [23]. However, the large residual stresses would also be generated at the direct bonding interface. The introduction of an interlayer with excellent ductility, such as the Ag-28Cu, would mitigate the stress distribution within the joint through its deformation. Moreover, the low melting point of the Ag-28Cu helped to reduce the thermal damage to these materials during joining.

In this study, the rapid SPS joining technique was conducted to join the WC-Co/40Cr joints using the Ag-28Cu interlayer. During the SPS joining, the samples can be heated at an extremely fast rate thanks to the direct electric heating process. Moreover, the pressure applied could also ensure the steady and even diffusion between the bonded materials. The bonding temperature might have a great influence on the element diffusion within the joint and the outflowing of the interlayer, further determining the bonding of the joints during SPS. Thus, the work aimed to clarify the evolution mechanism of microstructure and mechanical performance for the WC-8Co/40Cr joints under different joining temperatures (740 °C, 760 °C, and 780 °C). Through the optimization of the fast-joining parameter (for example, the joining temperature in this study), the solid joining obtained would further enhance the performance stability of the combination in harsh working conditions.

2. Materials and Methods

The base materials used in this study were the commercially available WC-8Co (wt.%) cemented carbides (Xiamen Golden Egret Special Alloy Co., Ltd., Xiamen, China) and 40Cr alloy steel (DongqiaoPinglin Metal Products Co., Ltd., Kunshan, China). The substrates were first cut into dimensions with a 10 mm diameter and 4 mm in thickness, using the electric discharge wire (EDW) cutting machine. The substrate blocks were then ground with the diamond disks (200 #, 400 #, 800 #, 1000 #, and 2000 #) to eliminate the oxidation surfaces. The interlayer used was the Ag-28Cu (wt.%) foil (Changsha TIJO Metal Materials Co., LTD., Changsha, China) with a thickness of 50 µm and a melting point of 780 °C. The Ag-28Cu interlayer was also cut into a 10 mm diameter with the metal puncher. Then the substrates and the Ag-28Cu foils were cleaned with an ultrasonic cleaning machine in the alcohol bath for 5 min to obtain the uncontaminated bonding surfaces. The joining process was conducted using the SPS-212H machine. Before joining, the WC-8Co/Ag-28Cu/40Cr sandwiches were assembled in the graphite mold, as shown in Figure 1a. The graphite papers were also placed between the joint assembly and the mold for more convenient demolding after bonding.

Before heating, the cabin was evacuated to 1.0×10^{-2} Pa, and the vacuum atmosphere was maintained during the entire joining process. Then, the 5 MPa axial continuous pressure was applied on the assembly with the press equipment installed within the SPS machine, as shown in Figure 1a. Then, heating and cooling processes for the bonding assemblies were carried out according to Figure 1b. The samples were first heated to 600 °C in 1 min. The temperature was then increased to the target temperature (740 °C, 760 °C, and 780 °C) with a heating rate of 20 °C/min. The samples were maintained at the bonding temperatures for 5 min to ensure that the samples were evenly heated. After the soaking process, the samples were cooled at the rate of 100 °C/min to 200 °C. Then the

samples were cooled by furnace cooling to room temperature. In this study, rapid joining between the WC-8Co and 40Cr steel was realized within 30 min, thanks to the fast heating (600 °C/min) and cooling rate (100 °C/min) adopted using the SPS machine. Compared with other joining methods, like brazing or transient liquid bonding [24,25], the SPS joining can be realized with shorter time or lower temperatures.

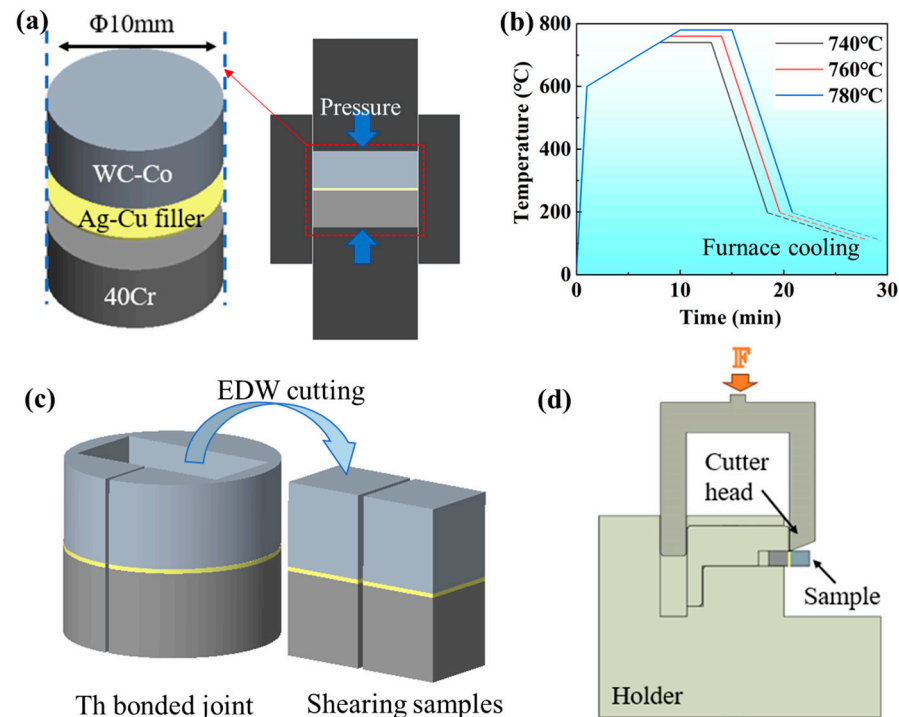


Figure 1. (a) Schematic diagram of sample assembly; (b) thermal cycle of the bonding process; (c) the shearing samples cut from the joint; and (d) schematic drawing showing the shear testing process.

After joining, the joints obtained were cut using the EDW cutting machine to observe the microstructure of the joint. The samples were ground with diamond disks from 200 # to 2000 #, and polished using the diamond suspensions to obtain the metallographic observation samples. The metallographic samples were cleaned in the acetone bath for 5 min, ultrasonically, to achieve uncontaminated surfaces. The microstructure of the samples was detected using the scanning electron microscopy (SEM, Hitachi S-4800, Tokyo, Japan) installed with the energy dispersive spectrometer (EDS, Oxford X-Max^N, Oxford, UK). The bonding strength of the joints was evaluated through $\tau = F/S$, in which the τ was the shear strength of the joint, the F was the maximum force applied on the joint, and the S was the bonded area of the shearing samples. The samples for shear testing were cut from the joint, as shown in Figure 1c, and the shearing process was performed using the electronic universal testing machine (MTS CMT4204, Eden Prairie, MN, USA) with a cutting mold, as shown in Figure 1d. During the shear testing, the forces were applied on the sample at a rate of 0.5 mm/min. The shear strength of the joints obtained at each processing temperature was averaged with 5 testing results. After shearing, the fractography of the sheared samples was also detected using the SEM to study the fracture mechanism.

3. Results

3.1. Typical Microstructure of the Joints Bonded at 760 °C for 5 Min

Figure 2 exhibits the microstructure of the 40Cr/Ag-28Cu/WC-8Co joints processed at 760 °C for 5 min. It can be seen that the joint is compact without any defects. The EDS mapping analysis was conducted to study the element distribution in the joint, and the

results are displayed in Figure 2c. It is shown that the interlayer is mainly composed of Ag and Cu elements, while some Fe and Co elements are segregated at the 40Cr/interlayer and the interlayer/WC-8Co interfaces. The segregation of Co and Fe at both interfaces reveals that intense element diffusion has occurred during the joining process. Furthermore, the element distribution also indicates the high affinity between Co and Fe elements. Moreover, no obvious W and C elements were detected in the interlayer, suggesting the high thermal stability of the WC-Co substrates during the joining. The magnified microstructure of the joint is shown in Figure 2b, in which the white phase A, gray phase B, and dark gray phase C are observed. Phases A and B compose the main body of the joint, while phase C is mainly distributed at the interlayer/substrate interface. In addition, phase D, located at the 40Cr interface, where Fe and Co are concentrated according to the element distribution results, is also analyzed.

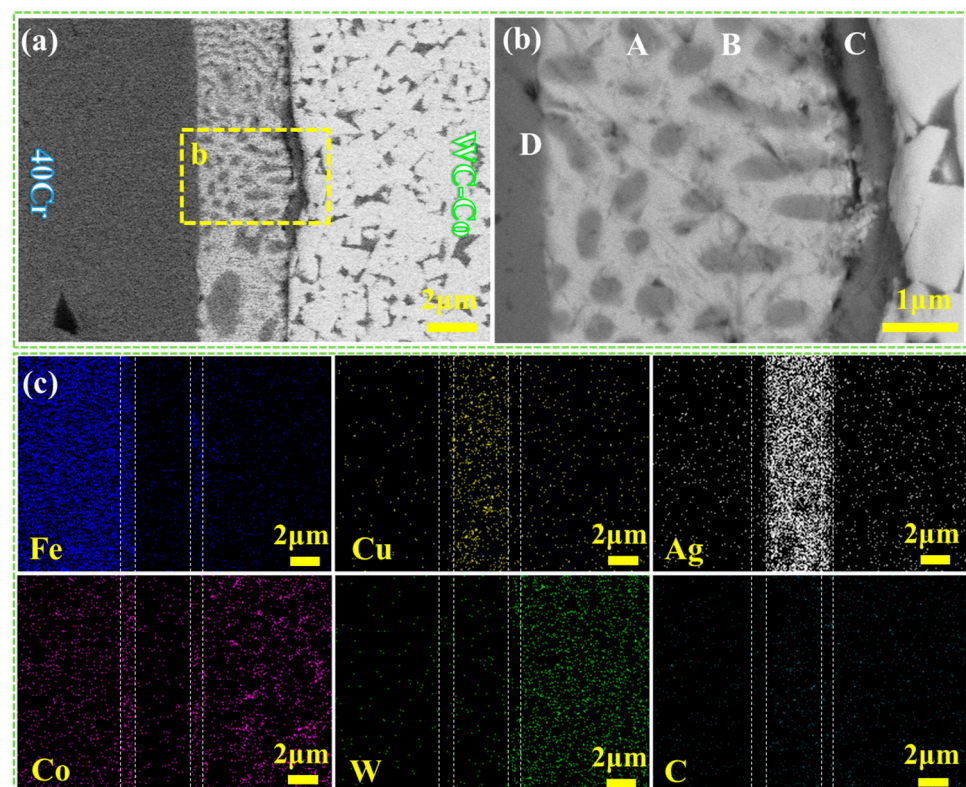


Figure 2. (a) Micromorphology and (b) the detailed microstructure and (c) the EDS mapping results of the 40Cr/Ag-28Cu/WC-8Co joints obtained at 760 °C for 5 min.

Figure 3 exhibits the EDS line scanning analysis results of the 40Cr/Ag-28Cu/WC-8Co joint. It is shown in Figure 3b that the Ag and Cu are concentrated in the interlayer, where the Fe, Co, or other elements are barely detected. It should be noted in Figure 3b that, at the 40Cr/interlayer and the interlayer/WC-8Co interfaces, the Ag and Cu intensity decreased dramatically, while both the Fe and Cu intensity increased. The Fe and Co enrichment at the interfaces implies the elemental exchange between the materials during the joining process. Moreover, the Ag and Cu elements are also inspected at these interfaces, indicating the element diffusion from the Ag-28Cu interlayer toward the substrates.

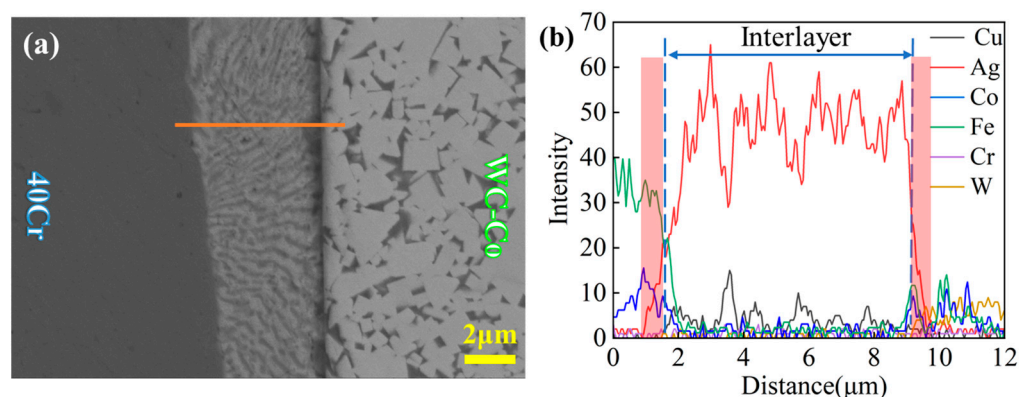


Figure 3. (a) The micromorphology of the joint, where the EDS line scanning was performed along the red line, and (b) the EDS line scanning results for the joint obtained at 760 °C for 5 min. (The pink area denotes the Fe and Co-enriched area).

The EDS analysis was performed to further identify the phases formed in the joints, and the results are listed in Table 1. It can be seen that phase A is mainly composed of Ag (70.6 at.%) and Cu (29.4 at.%), which suggests the Ag(s,s) formed. In phase B, the Cu content is 75.3 at.%, therefore, phase B is deduced to be the Cu(s,s). Phase C contains mainly the Fe (63.8 at.%) with some Co (24.3 at.%) and W (11.9 at.%). The Fe and Co have high mutual solubility in each other, and no intermetallic precipitates should be formed according to this composition. Therefore, the phase C should be the Fe (s,s) [26]. Phase D at the 40Cr/interlayer interface shows a similar chemical composition to phase C, which is also the Fe(s,s).

Table 1. The EDS analysis results for each phase of Figure 2.

Spots	Compositions (at.%)					Phases
	Ag	Cu	Fe	Co	W	
A	70.6	29.4	-	-	-	Ag(s,s)
B	24.7	75.3	-	-	-	Cu(s,s)
C	-	-	63.8	24.3	11.9	Fe(s,s)
D	1.9	6.8	71.2	20.1	-	Fe(s,s)

From the above analysis, the microstructure of the WC-8Co/Ag-28Cu/40Cr joint processed at 760 °C for 5 min is exhibited as: 40Cr/Co-enriched Fe(s,s) interfacial layer/Ag(s,s) + Cu(s,s)/Co-riched Fe(s,s)/WC-8Co.

3.2. Effects of Bonding Temperature on the Microstructure of the Joints

Figure 4 displays the micromorphology of the 40Cr/Ag-28Cu/WC-8Co joints processed at three different temperatures for 5 min. When bonded at 740 °C, some unbonded defects were found at the 40Cr/interlayer interface, as shown in Figure 4a. When increasing the bonding temperature to 760 °C, the thickness of the interlayer is slightly reduced. Furthermore, the sound bonding is exhibited at the 40Cr/interlayer interface, thanks to the intensified element diffusion at higher bonding temperatures. While the bonding temperature is increased to 780 °C, which reaches the melting point of the Ag-28Cu interlayer, the Ag(s,s) and Cu(s,s) barely exist within the joint, as shown in Figure 4c.

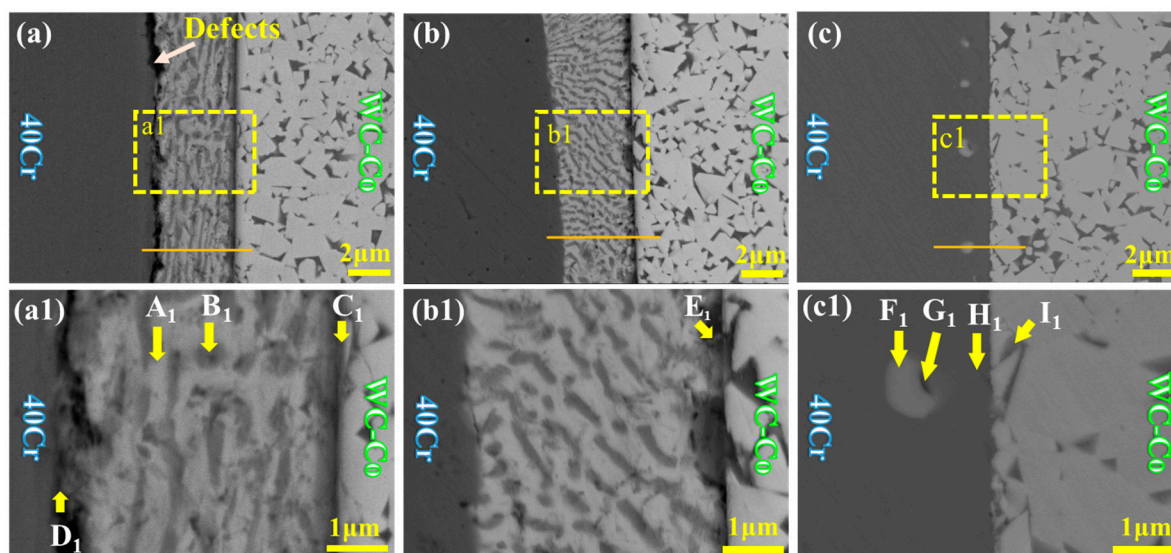


Figure 4. Microstructure and enlarged morphology of joints bonded at different temperatures for 5 min: (a,a1) 740 °C; (b,b1) 760 °C; and (c,c1) 780 °C (The lines means the positions of the EDS line scanning).

Figure 5 shows the results for the EDS line scanning analysis performed along the line in Figure 4. It can be seen that when bonded at 740 °C and 760 °C, the element distribution across the joint exhibits the same feature. At the substrate/interlayer bonding interface, the Fe and Co are enriched while the Ag and Cu are reduced. Moreover, it can also be seen in Figure 5 that with the increasing bonding temperature, the Fe and Co interfacial enrichment was also intensified (revealed by the slightly thickened interfacial element enrichment). When the bonding temperature is increased to 780 °C, the Fe and Co domains the while joint, with traces of Ag element detected. In such a case, the layered structure within the joint is changed to nearly direct bonding between the 40Cr and WC-8Co.

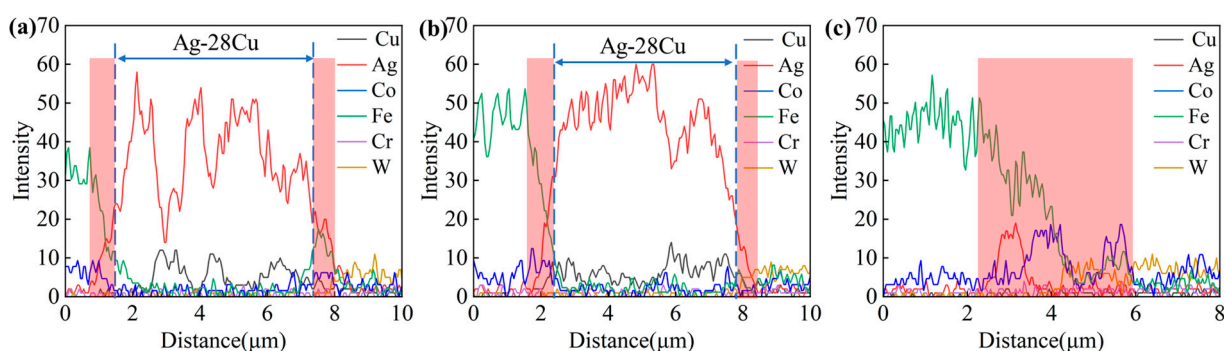


Figure 5. EDS line scanning results for the joints bonded at (a) 740 °C; (b) 760 °C; and (c) 780 °C. (The pink area denotes the Fe and Co-enriched area).

Figure 4(a1–c1) demonstrates the magnified microstructure of the joints, in which the phases are marked as A₁–I₁. The EDS analysis results for the phases in are summarized in Table 2. It can be seen that in the joints bonded at 740 °C, the bonded area is mainly composed of Ag(s,s), Cu(s,s), and the Fe(s,s) interfacial layers, which is consistent with the joints bonded at 760 °C. However, when the bonding temperature is increased to 780 °C, the joint consists mainly of Fe(s,s) with a few particles Ag(s,s) phases. Moreover, the Cu(s,s) is not detected according to the EDS analysis results, because the Cu element is dissolved in the joint. Therefore, it can be concluded that no new phase is precipitated, whereas

the morphology of the joint changed a lot when in the 40Cr/Ag-28Cu/WC-8Co joint was bonded at different temperatures.

Table 2. The EDS analysis results for the phases in Figure 4.

Spots	Compositions (at.%)						Phases
	Ag	Cu	Fe	Co	W	Cr	
A ₁	70.2	29.8	-	-	-	-	Ag(s,s)
B ₁	49.1	50.9	-	-	-	-	Cu(s,s)
C ₁	-	5.8	38.5	11.5	44.3	-	Fe(s,s)
D ₁	3.8	10.2	74.4	10.5	1.1	-	Fe(s,s)
E ₁	4.1	6.1	65.0	22.6	2.2	-	Fe(s,s)
F ₁	65.4	10.4	24.2	-	-	-	Ag(s,s)
G ₁	30.4	5.2	57.9	6.5	-	-	Fe(s,s)
H ₁	-	2.8	64.6	29.0	2.6	1.0	Fe(s,s)
I ₁	-	-	30.5	27.2	42.3	-	Fe(s,s)

3.3. Mechanical Properties of the Joints

Figure 6 shows the shear strength of the 40Cr/Ag-28Cu/WC-8Co joints bonded through the SPS method at different temperatures. It is shown that the shear strength of the joints is first increased and then decreased with the increase in bonding temperatures. When the bonding temperature is 740 °C, the shear strength of the joints is 196 MPa. When increasing the bonding temperature to 760 °C, the joint shear strength reached the peak value of 236 MPa. With increasing the bonding temperature to 780 °C, however, the shear strength of the joints shows a dramatic decrease to 173 MPa.

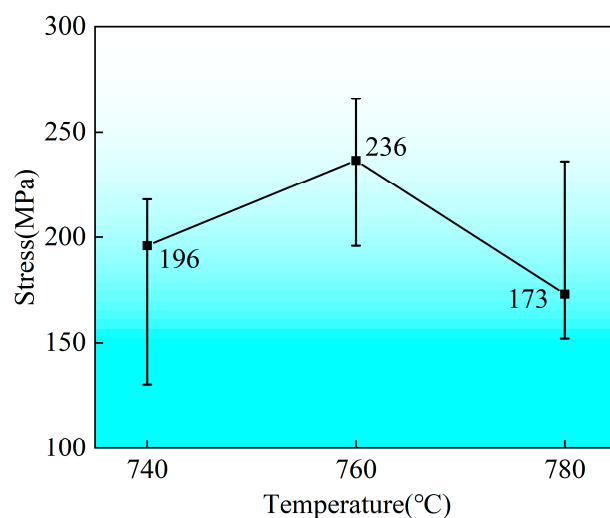


Figure 6. Shear strength of the joints bonded at different temperatures.

Figure 7 displays the fracture morphology of the joints after shear testing. It can be seen in Figure 7a that the joints obtained at 740 °C fractured directly at the 40Cr interface, which shows a straight propagating path. Some Ag-28Cu interlayer with elongated dimples is also observed on the fracture surface, as shown in Figure 7a1. When the temperature is increased to 760 °C, the fracture occurs within both the WC-8Co and the interlayer. On the fracture surface, the dimples found reveal plastic fracture, and the WC particles reveal the brittle intergranular fracture. When the temperature is increased to 780 °C, the fracture also propagates within the WC-8Co and the 40Cr interface. And some dimples and WC grains found at the fracture surface also reveal the mixed fracture mold.

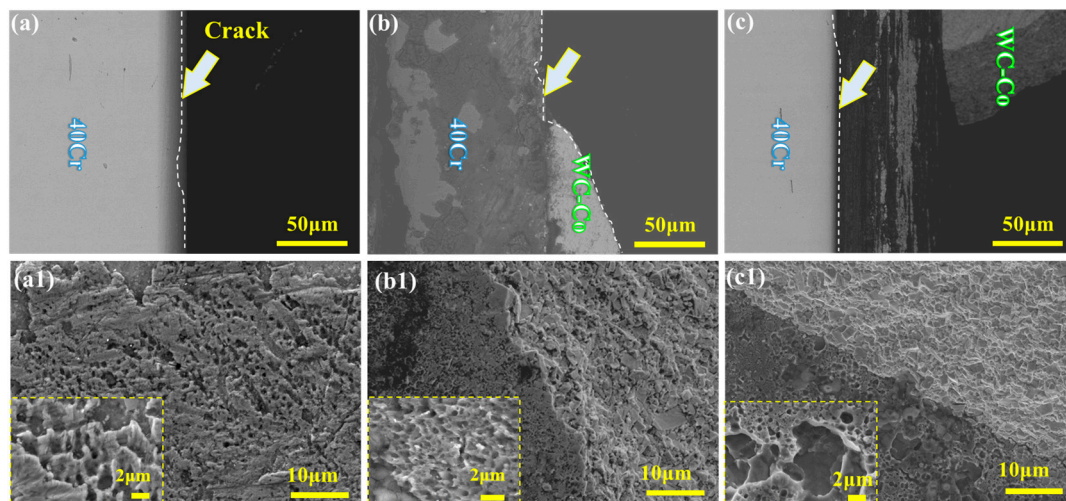


Figure 7. Fracture path and the of the and the fracture surface morphology of the of the joints bonded at (a,a1) 740 °C; (b,b1) 760 °C; and (c,c1) 780 °C after shear testing (The arrows points the location of the cracks happened in the joints).

4. Discussion

4.1. Forming Mechanism of the Joints During Bonding

The schematic drawing in Figure 8 demonstrates the joining mechanism of the joints during the heating and cooling process. During the heating process, element diffusion happened between the 40Cr steel, the Ag-28Cu interlayer, and the WC-8Co substrates, under the effects of electric heating and pressure. During this process, the Fe element diffused toward the interlayer and the WC-8Co substrate under the concentration gradient. Similarly, the Co diffused from the WC-8Co into the interlayer and toward the 40Cr steel substrate. Also, the Ag and Cu diffused from the interlayer into both substrates. It should be noted that, due to the lower melting point of the Ag-28Cu interlayer, the elements from the substrates diffused much quicker into the near-molten interlayer during heating. Comparatively, due to the solid and compact structure of the steel and the cemented carbide, element diffusion into the substrates was quite hampered. Therefore, with the diffusion process kept on, the Fe and Co gradually diffused across the interlayer and enriched at the interfaces, promoting the formation of the Fe(s,s) high-temperature phase.

During the soaking process at 760 °C, the Fe(s,s) interfacial layer gradually grew as the element diffusion continued. However, it should also be noted that, with the redistribution of the elements, the element diffusion process should be retarded due to the reduced concentration gradient. Moreover, the solid Fe(s,s) interfacial layer formed would also hamper the diffusion process. Under this condition, the growth of the Fe(s,s) was slowed during the soaking and cooling processes.

In the interlayer, with the Fe and Co high-temperature elements involved, the Ag-28Cu recrystallized. During the cooling process, the Ag(s,s) and Cu(s,s) gradually grew, and finally, the joint was formed.

When bonded at lower temperatures (for example, 740 °C in this study), the element exchange was decelerated, which resulted in the defects at the 40Cr/interlayer interface. Furthermore, the Fe(s,s) interfacial layers were also reduced. With the temperature increased to 780 °C, the Ag-28Cu was melted during bonding. In this condition, the 40Cr and WC-Co dissolved into the molten pool, forming the Fe(s,s). Under the pressure applied, the liquid was squeezed out of the interlayer, leading to the dramatic reduction of the Ag(s,s) and Cu(s,s), and finally, the Fe(s,s) was dominant in the interlayer.

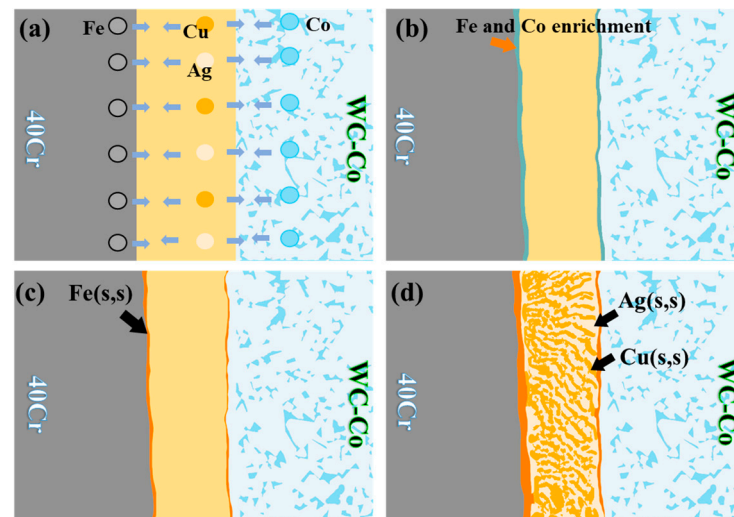


Figure 8. Schematic drawing illustrating the joining mechanism: (a) element diffusion; (b) Fe and Co element enrichment at the interfaces; (c) precipitation of the Co-enriched Fe(s,s) phase; (d) recrystallization of the interlayer.

4.2. Relationship Between the Microstructure and Mechanical Properties of the Joints

In the dissimilar bonded joints, the mechanical properties of the joints were generally governed by three factors: interfacial bonding strength, mechanical properties of the interlayer, and the residual stresses. In this study, the 40Cr and WC-8Co were bonded with the Ag-28Cu interlayer through the SPS technique at 740 °C, 760 °C, and 780 °C. It should be noted that no defects were formed in the interlayer, indicating that the interlayer should not be the weak point of the joint.

When bonded at 740 °C, the temperature was way below the melting point of the Ag-28Cu interlayer. Due to the sluggish diffusion process in the solid interlayer at 740 °C, the 40Cr/interlayer was not tightly integrated. Therefore, during the shear testing, the joints fractured at the corresponding interface. As shown in Figure 9, the joint underwent small plastic deformation and fracture early with the shearing loading applied. In such a fracturing mold, the cracks initiated and propagated along the defects at the interface, as depicted in Figure 7a.

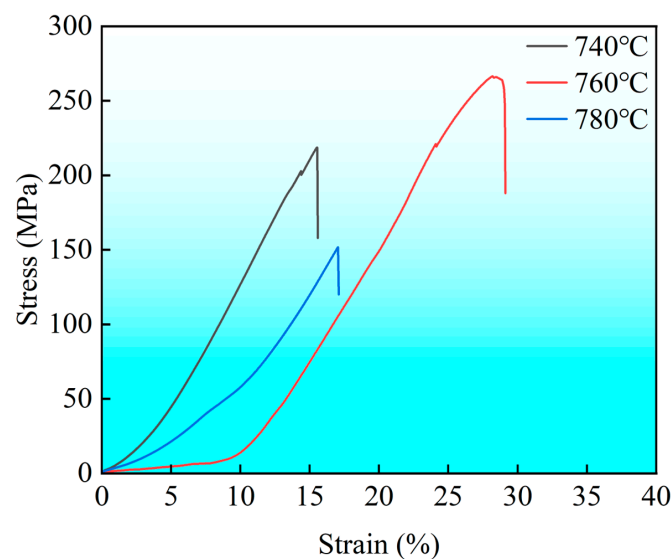


Figure 9. Stress–strain curves of the joints bonded at different temperatures during the shearing process.

When the temperature was increased to 760 °C, the interfacial defects were eliminated, as also mentioned in [27], which enhanced the interfacial bonding strength. Under these conditions, the residual stresses became the main factor influencing the bonding strength of the joints. Meanwhile, the cracks would initiate within the WC-8Co and propagate along the bonding interface, as shown in Figure 7b. While further increasing the temperature to 780 °C, the bonding area was predominated by the Fe(s,s), which greatly reduced the ductility of the joint. The Ag-28Cu interlayer could mitigate residual stresses through plastic deformation by itself. The reduction of the Ag and Cu plastic phases caused a decrease in the plastic deformation ability of the joint. In such a case, the residual stresses would also be intensified due to the reduced deformation ability of the joint during cooling. Under such circumstances, the largest residual stresses were believed to generate at the WC-8Co interface, which damaged the bonding strength of the joint. Under the shear loading, the joint fractured directly at the bonding interface, where the largest residual stresses existed.

Therefore, it could be concluded that when bonded at a relatively low temperature, the poorly bonded interface was the weak point of the joint. Increasing the bonding temperature could strengthen the interfacial bonding strength while increasing the pernicious residual stresses at the same time. Therefore, when bonded at the optimized temperature (760 °C in this work), the highest bonding strength was obtained. The work performed provided a new way for the rapid and low-temperature joining of the WC-Co cemented carbides and the alloy steels, which could further expand their industrial utilization.

5. Conclusions

In this study, the Ag-26Cu filler foil was used to bond the 40Cr and WC-8Co through the SPS technique at different temperatures. The analysis results for the microstructure and mechanical properties of the results are revealed below:

- (1) The microstructure of the joints bonded at 760 °C was characterized as: 40Cr/Co-enriched Fe(s,s) interfacial layer/Ag(s,s) + Cu(s,s)/Co-riched Fe(s,s)/WC-8Co. The Fe(s,s) formed with realized the interfacial bonding of the joint, while the Ag and Cu provide good plastic deformation ability.
- (2) A higher bonding temperature would help to reduce the interfacial defect, which therefore strengthens the joint bonding strength. However, the bonding temperature should be controlled as the outflow of the filler would cause higher residual stresses, which would damage the joint strength.
- (3) In this study, fast joining between the WC-8Co and 40Cr steel was realized through the SPS joining method. The evaluation of other mechanical properties (like impact toughness) of the joints should be our focus in the next step. Furthermore, the post-bonding heat treatment [28] is believed to have a great influence on the microstructure, mechanical properties, as well as residual stresses of the joints. Therefore, the effects of heat treatment on the WC-8Co/40Cr joint should be carefully studied.

Author Contributions: Conceptualization, S.W. and H.X.; Methodology, S.W., C.Y. and X.L.; Validation, S.W.; Formal analysis, S.W., X.L. and H.X.; Investigation, S.W., C.Y., X.L. and H.X.; Resources, H.X.; Data curation, C.Y. and X.L.; Writing – original draft, S.W. and H.X.; Writing – review & editing, X.L. and H.X.; Project administration, S.W. and C.Y.; Funding acquisition, S.W. and H.X. All authors have read and agreed to the published version of the manuscript.

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