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Evaluation of an AlCrN coated FSW tool

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ABSTRACT

Purpose: This paper aims to evaluate the wear performance of a physical vapor deposition (PVD) coating on cemented carbide (WC) tool used in friction stir welding FSW processing of Ti alloy sheets.
Design/methodology/approach: A coating of AlCrN material was applied to a WC tool in order to increase its wear resistance, thermal shock stability and hot hardness. In comparison to the conventional coatings, the AlCrN coating system had a higher resistance to abrasive wear as well as higher hot hardness and oxidation resistance. FSW processing of Ti with a coated WC tool was expected to have better performance than an uncoated tool. Back Scattering Electron (BSE) imaging mode at scanning electron microscope was used to determine the main mechanism of tool wear, which was found to be hot adhesion and inter-diffusion of tool constituents with the workpiece materials.
Findings: The tool degradation was evaluated by scanning electron microscopy in order to observe the main tool wear mechanism. The real contribution of the (Al,Cr)N coating layer could not be correctly evaluated, since there is no residual trace of its components at the worn tool. What was probably found left from the coating layer was the N component which formed the nitride TiN observed by EDS mapping. The parameter conditions were probably too severe, overcoming the layer limit strength.
Research limitations/implications: The research were carried out as a preliminary evaluation and this initial results in the need of a further analysis that should be performed looking for a suitable tool material and coating optimization for the FSW processing of titanium alloys.
Practical implications: Despite being successfully used in other manufacturing applications like machining operations in which friction and temperature are also high, the WC tool material and the coating had an unsatisfactory wear resistance, and the AlCrN coating was totally worn during the FSW processing. This suggests that new materials and coatings are still needed for FSW tools.
Originality/value: FSW process is gaining importance as an industrial joining method, but the tool wear is still an important challenge to achieve efficient and economic operation. Because of the low thermal conductivity and high chemical reactivity of Ti, tools wear rapidly due to high temperature and strong adhesion. In order to achieve higher processing speeds, reducing heat at the interface tool/work material is required, as is the use of tool materials that have little or no chemical affinity.
Keywords: Friction stir welding; FSW, AlCrN coating; WC tool; Wear; Tribology; Titanium alloy

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1. Introduction

1.1. Friction Stir Welding (FSW)

Friction Stir Welding (FSW) is a solid state joining process, which eliminates problems associated with material melting and solidification such as cracks, residual stresses and distortions generated during conventional welding. It was invented in 1991 at TWI (The Welding Institute), initially for aluminum joining. Comprehensive reviews about FSW process can be found in [1-5]. Its most important advantages are: ease of automation, less distortion, lower residual stress and good mechanical properties in workpiece [2]. FSW albeit originally intended for aluminum alloys, it is investigated in a variety of metallic materials [4].

The basic concept of FSW is a non-consumable rotating tool, especially designed with a geometry consisting of a pin and recess (shoulder). The tool is inserted, spinning on its axis, at the adjoining edges of sheets or plates to be joined, and then it travels along the joining path line producing a welding-like region.

Fig. 1. illustrates the process for the tool and the plate, typical steps of the process: i) downward motion to penetrate the material; ii) penetrating the material; iii) time for the heat generation for deformation; iv) linear movement on the part toward the processing direction; v) end of processing and tool retraction.

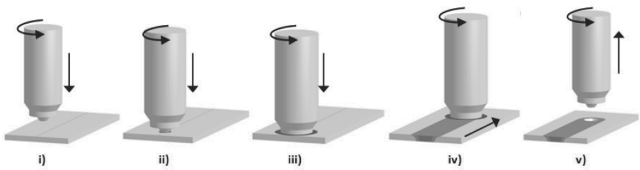


Fig. 1. FSW process steps [3]

The tool rotation axis defines an angle of inclination with the components to be welded. This angle is used for receiving the material to be processed at the tool base and to promote the gradual forge effect imposed by the shoulder during the passage of the tool. This prevents the material plastic flow at the tool lateral, ensuring weld closure on the back of the pin.

1.2. Tool materials and coating

Tool wear in the FSW of titanium and high strength steel is a remarkable problem and often leads to the use of tungsten-rhenium (W-25%Re) alloys to overcome this problem. This implies high operation tool costs due to the rare rhenium component. An alternative is the use of hard materials based on tungsten carbides alloys (WC), which are highly employed for conventional machining, easily found in various sizes and compositions and their processing technology is widespread.

Another subject scarcely evaluated in FSW process articles is tool coatings, providing a FSW tool with protective coating layers, which may be an alternative to provide specific properties necessary at the FSW process event. It is well known that, the primary function of the hard material layer is to inhibit contact between materials, thereby reducing tool wear, which can mainly be caused by adhesion, abrasion, diffusion and oxidation [6-9].

In general, adhesion and diffusion and oxidation at high temperatures determine tool wear [6]. The hard coatings processed by PVD (physical vapor deposition) and CVD (chemical vapor deposition) techniques are efficient means to increase the durability of tools made from cemented tungsten carbide; the hard material layer improves wear resistance, reduces adhesion between the tool and the workpiece and acts as a diffusion barrier.

For this research, a nitride (Al, Cr)N coating was chosen; such coatings have high hardness and resistance to abrasion, higher than conventional TiN coatings, and can thus be applied to cover cutting edges. (Al, Cr)N coatings present high thermal stability, and their maximum operating temperature is 1100ºC [7, 15-16].

A typical coating layer is shown in Fig. 2. It can be observed from the fractures of (Al, Cr)N coatings that this coating is also multilayer, typical for multi-component coatings obtained through the application of separate sources of metal pairs Chromium and Aluminum [7].

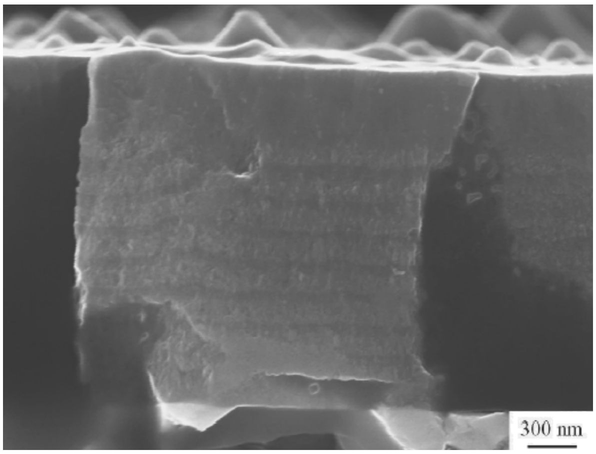


Fig. 2. Micrograph of the (Al, Cr) N coating deposited onto the sintered carbide substrate [7]

1.3. Tool wear in high strength alloys

Evaluation of wear on FSW tooling for high strength alloys, especially titanium alloys, has been reported in recent years by some researchers [10-13]. Zhang et al. [10] worked commercial pure (CP) titanium with a FSW tool made of polycrystalline cubic boron nitride (pcBN). On the weld surface, pcBN tool debris was found and Ti borides was observed only on the top surface of the welded region, which implies that the pcBN tool wear occurs more significantly in the vicinity of the top surface during FSW. The tool wear was mainly caused by incomplete solving of boron and nitrogen in Ti. Sato et al. [11] developed a cobalt-based tool alloy for high strength materials such as steel and titanium. The Co-based tool was alloy strengthened by precipitating intermetallic, $Co_3(Al,W)$ at high temperatures and tested in steels and titanium alloys. In particular for the Ti-6Al-4V alloy, the tool wear was low and the weld quality was good. The wear mechanism was not discussed in their research. Thompson and Babu [12] evaluated three tools based on tungsten alloy, material A: W with 1.0%La_2O_3, Material B: W-25%Re and material C: alloy with a 70%W+20%Re+10%HfC composition. This HfC addition has a significant impact on high-temperature strengths. Thompson & Babu [12] concluded that the primary degradation mechanism of material A was plastic deformation; material B suffered degradation by twinning mechanism and the primary degradation mechanism of material C was intergranular failure.

Recently, Buffa et al. [13] carried out an extensive research into FSW processing of the Ti-6Al-4V alloy, they worked with two WC-Co cemented carbide tools: WC-4.2%Co, WC-12%Co and a W-25%Re alloy tool. For the tool material WC-4.2%Co, due to its condition of brittleness, fracture was the main tool failure mechanism; on the other side, for the WC-12%Co tool, the increasing on the cobalt binder phase provided an increase of tool toughness while keeping the overall hardness in a reasonable condition; deformation occurred in the shoulder and at the pin together with adhesive wear degradation. The W-25%Re showed to have the lowest wear degradation; the authors left the correct evaluation of the abrasive and adhesive wear on the W-25%Re tool for further research.

2. Materials and experiments

Aiming at developing a tool material that supports the FSW processing of titanium sheets, a tool was prepared with a 20 mm diameter shoulder, 5 mm diameter tapered pin with a 30° angle in a cemented carbide (WC-Co) material. For this research, a WC-6%Co alloy was chosen to construct the FSW tool, which is a cemented carbide class largely employed for conventional machining tools. This metallic matrix composite is successfully used for processing holes in metal sheet in the automotive industry for housing and screw clamps vehicle assembly. It was the first choice because the processing temperatures involved are in the order of 900°C to 1000°C. Titanium FSW process submits the tool to severe strain, friction and temperature; the latter estimated at up to 900°C [14].

An (Al, Cr)N coating was applied by the PVD process at the pin and shoulder tool; the coating layer height was estimated to be 5 µm. The processing material was a titanium alloy Ti-6Al-4V, the sheet size was 260 mm long, 50 mm in width and 4 mm thick.

Fig. 3. presents the basic geometry for a FSW tool employed in this work for friction stir welding of the titanium alloy where: R_s is the shoulder radius, R_p is the pin base radius, R_{pt} is the pin point radius L_{pin} is the pin height and α is a tap angle. According to Edwards and Ramulu [5] a conical tool is needed because of the low thermal conductivity of titanium. A cylindrical pin tool is not indicated for titanium because the heat generated in the shoulder is not able to flow to the root of the joint and allow the mixing of material in the lower plate.

The FSW parameters for these specific wear resistance tests were set at 1500 rom tool rotation and 50 mm/minute feed; the testing tool should be able to make the joining without wearing and without breaking. The test was conducted without any cooling at the tool in order not to decrease the process temperature.

To minimize vibrations and to provide an initial guide for the tool pin, a previous pilot 1.60 mm deep hole was made with a twist drill. The drill diameter (4.8 mm) was selected to be smaller than the tool tip (5.0 mm); therefore, the tip of the tool, while executing the penetration, would generate friction with the lateral of the hole, supplying heat to the initiation of the FSW process.

Figs. 4a, 4b and 4c present an overall look of the set-up used for this experiment. In Fig. 4a, the coated WC-6%Co tool is presented. The (Al, Cr)N coating is grey as is the tool body; the pin and shoulder region received the coating. Fig. 4b presents the fixture set for the titanium workpiece sheet on the machine table; a supporting plate especially designed for the test was fixed, and a clamping bar with M10 fasteners was used to keep the titanium sheet fixed. In Fig. 4c, the tool fixed at the machine head is rotating and advancing through the sheet.

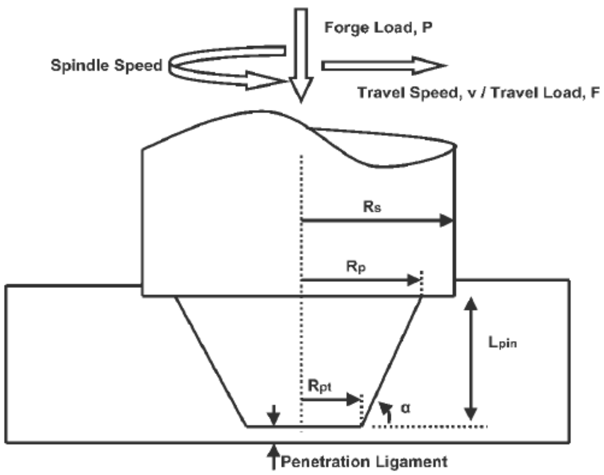


Fig. 3. Basic geometry for FSW tool [5]

The machine used for the FSW process was a controlled numeric computer (CNC) machine from Mazak manufacturer type FJV 35-60, portic type. It is a heavy machine (about 13 tons) employed in machining steels components, and has a double column construction (the machine tooling head is not in balance) which provides stiffness during the FSW process.

For a precise evaluation of the wear mechanism of the tool pin and shoulder region, scanning electron microscopy was employed using a Camscan CS3200LV microscope to produce Secondary Electron Images (SEI) and element images from energy-dispersive X-ray analysis (EDS).

3. Experimental results

The workpiece was successfully processed as seen in Fig. 5, in which a 100 mm long processed region can be observed. The weld surface was regular with the exception of the formed burrs.

The dark finish is due to not using a protective gas (inert gas, e.g. argon) to keep the atmosphere near the event free of oxygen. The oxygen present in the atmosphere together with the temperature provided an oxide layer over the processed region.

This option was chosen to ensure an extreme environment condition at the WC tool during the process.

Figs. 5a and 5b show the worn tool after the FSW process. In Fig. 5a, some color difference is observed, indicating that some oxidation happened at the pin during the process; from this angle, the pin tool is almost indistinguishable. In Fig. 5b, it is clear that a high deformation process occurred at the pin and shoulder; especially, the tool pin lost its original geometry.

Probably more than one wear mechanism is acting together due to the pressure and temperature at the tool shoulder and pin, such mechanism caused the degradation of tool pin, tool shoulder and enlargement of the shaft diameter. Where the highly deformed pin tip can be seen

4. Discussions

From the tool pin and shoulder surface element mapping with EDS (Fig. 6b), the titanium plate material was observed to adhere after FSW processing.

Fig. 7a shows that the pin underwent a fragmentation process possibly during plunging into the workpiece and due to strong adhesion of the workpiece material.

This is a critical moment for the FSW process, as the region being processed is not in plasticity state; thus, it is not undergoing deformation due to the energy required to enter the steady state process. At this point, the tool should provide toughness in order not to suffer an initial fracture.

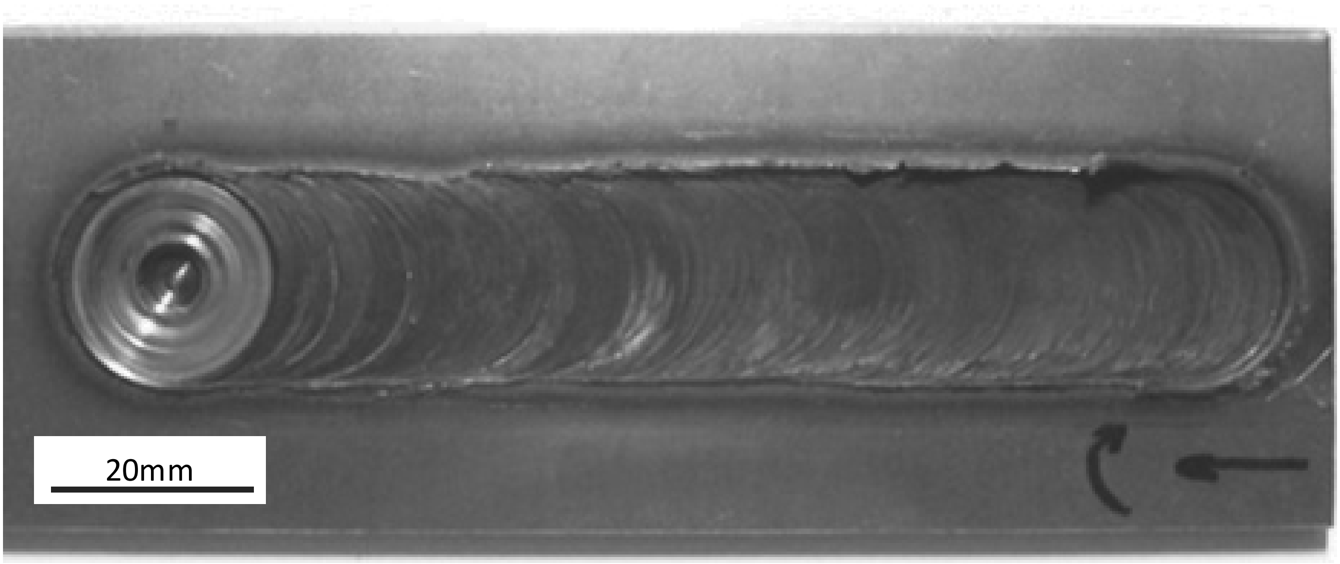


Fig. 4. Aspect of the FSW processed region of the Ti-6Al-4V sheet

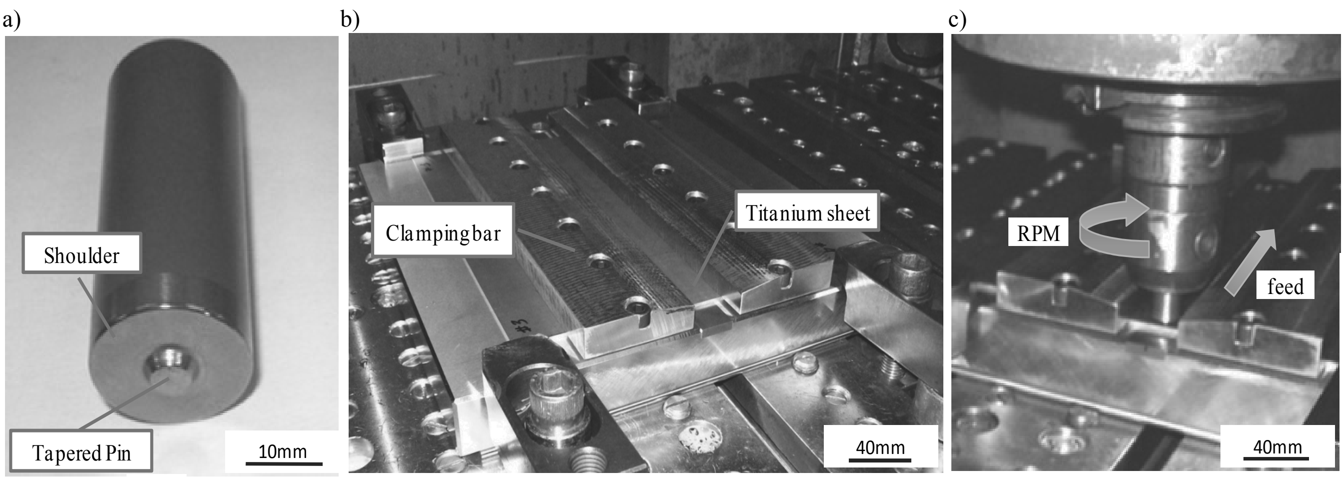


Fig. 5. (a) Tool design showing the pin and shoulder features, (b) fixture device used for the experiment and (c) the tool fixed in the machine spinning and advancing on the titanium sheet

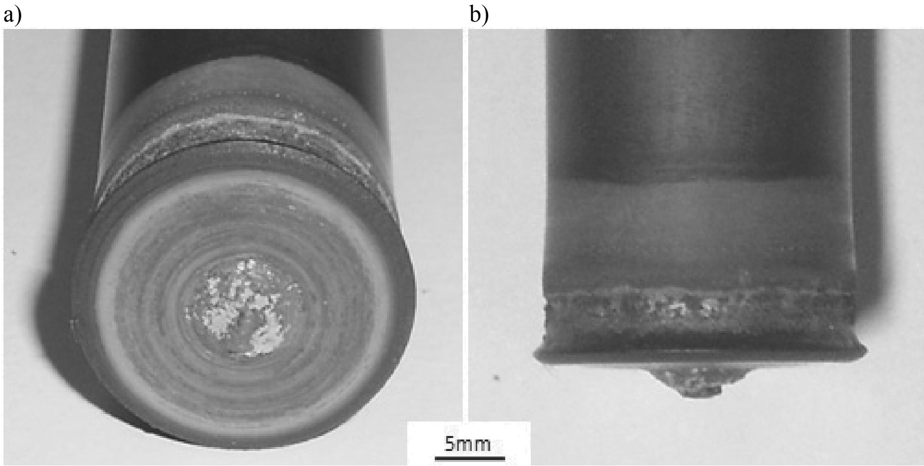


Fig. 6. (a) Front view of the worn tool after the FSW process, (b) side view of the worn tool

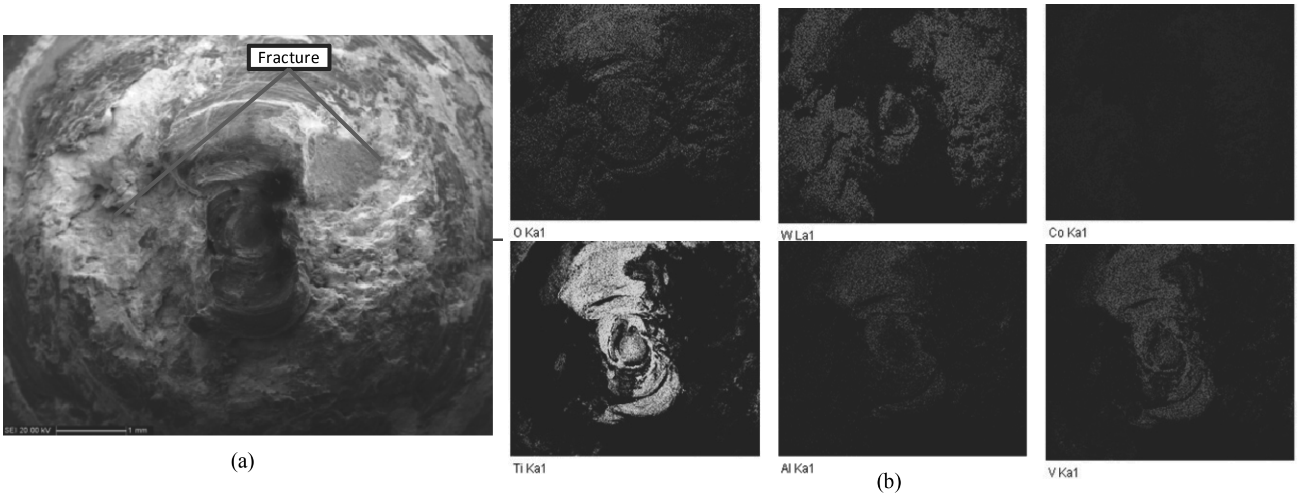


Fig. 7. (a) Micrograph of tool pin showing a fractured region, (b) EDX maps of tool pin showing the components found

The process parameters can also influence the plunge movement; if the plunge feed at the tool is large enough to overcome the tool compressive strength, it will undergo rapid degradation at the pin. In Fig. 7b, EDS mapping shows that the components found on the surface, besides the W and Co which derives from tool composition, are Ti, Al and V from the welded material. Oxygen was also found indicating that there was oxidation in the region, which was expected, because no shielding gas was used.

The presence of material workpiece constituents on the surface of the tool indicates that an adhesion process occurred. The mapping indicates that the largest amount of adhered material was found at the non-fractured tip, while in the fractured region, the original constitution of the tool is observed. Traces of the (Al, Cr)N layer applied to the tool were not found, which indicates the possibility of its being eliminated during FSW processing. Although the Al component can be seen, present at the composition of the workpiece and layer, it alone does not explain the layer existence because no trace of Cr or N forming the nitride (Al, Cr)N, could be observed.

In the micrograph of Fig. 8a, well-defined materials regions are observed; although it is difficult to distinguish the correct composition, it is possible to observe that the surface is uneven and does not provide a uniform topology. Through an EDS analysis at the tool shoulder, the bands of Ti, Al and V can be clearly identified, at the central region of the tool, while at its edge W and Co (Fig. 8b) are observed. The fact that a lower adhesion of workpiece material is found at the end of the shoulder region compared to the central region can be explained by three concurrent factors.

The first, and most dominant, is that this region has suffered extensive deformation with the increase of temperature and vertical compression during the FSW processing; it is possible to see such deformation in Fig. 9.

This region had virtually no contact with the workpiece or had contact with it only at the beginning of the process. The other two are related to the decrease in temperature and tangential velocity at the shoulder end. At the latter point of contact between tool and workpiece, the lowering temperature and increasing speed (it is the highest tangential velocity region of the tool) forces the FSW process to become "cold", i.e., which complicates the diffusion mechanisms and adhesion of the workpiece material to the tool.

The presence of oxygen in this region also indicates that all the tool regions underwent an oxidation process which probably arose from the high temperature reached during the FSW processing. No traces of the (Al, Cr)N layer applied to the tool were found; the presence of a workpiece material layer adhered could hinder the view of the (Al, Cr)N layer; due to this fact, an analysis of a deeper layer was required. For that, a cross-section was executed on the tool, and this section was made at the exact center of the tool as shown in Fig. 9a and Fig. 9b.

In Fig. 9a, a back-scattered electron image (BSE) in the shoulder region of the tool is presented and in Fig. 9b, we have a micrograph of the tool fractured pin region.

The BSE micrograph in Fig. 9a shows a cross section of the end region of the shoulder; the BSE allows visualizing distinct regions on the bottom shoulder of the tool. The BSE technique allows separating heavier materials (W) in a lighter colored region, while lighter materials have darker color regions.

In Fig. 9a, a specific interaction can be verified to occur between the materials in a part formed as "Region A"; a magnification of this area is mapped and presented in Figs. 10a and 10b. In Fig. 10a, an BSE view shows two distinct regions, the lighter one comprises the tool material (W) and the darker one with an average thickness of 50 µm consisting of constituent materials of the titanium workpiece. In the interface between these two regions (workpiece and tool), there is a transition zone comprising corrugated formations which are a result of severe deformation undergone by the tool during the FSW processing.

The mechanism for this degradation takes place solely by the action of temperature and pressure at the end of the tool which rotates and advances. Corrugation occurs from the tool center to the shoulder end, accordingly decreasing in intensity at the shoulder end region, where the temperature tends to be lower for being in contact with the environment.

Another important observation to be made in Fig. 8b is checking the component N in clear combination with Ti to form TiN.

The probable source of the N layer is from the (Al, Cr)N layer deposited before processing with FSW. This N is trapped during the process, preferably forming a solid solution with Ti and completely eliminating the Cr, and partially Al, as seen in the mapping of Fig. 10b.

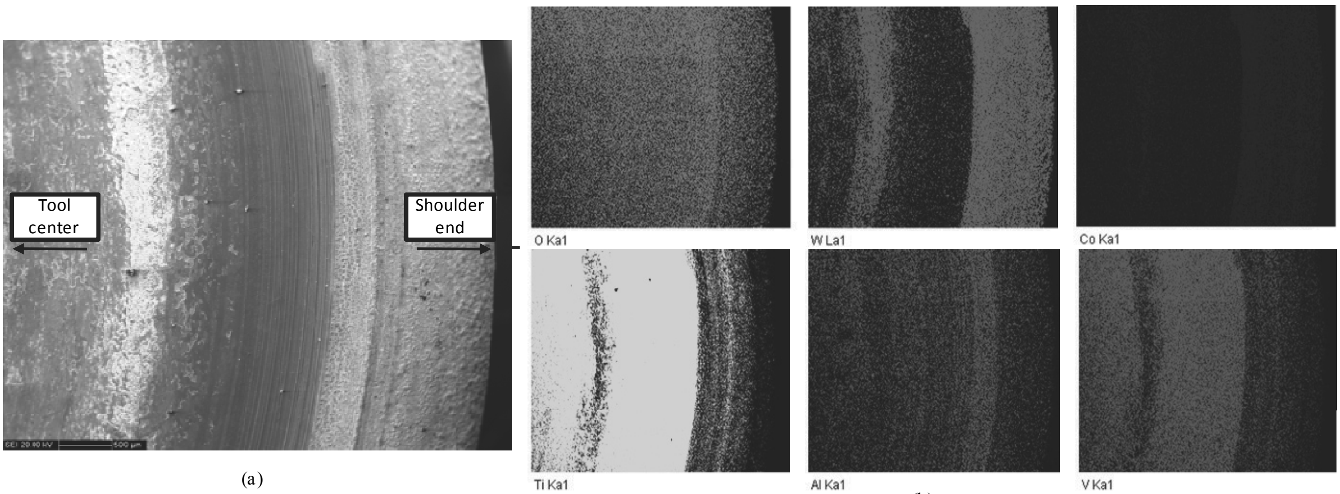
The titanium element has an incomplete layer in its electronic structure which allows the formation of solid solutions with most alloying elements which have a size factor within ± 20% [17]. Elements such as C, O, B, N and H will form interstitials structures because of the large difference in size between its atoms and the Titanium atom.

Still in Fig. 10a, important mechanism acting on the interface workpiece and tool can be identified. "Region B" is magnified in Figs. 11a and 11b. In Fig. 11a, a clear diffusion mechanism is verified to occur between the tool materials to the workpiece material.

The melting point between WC and Co is about 1300°C [18]. This temperature was reached at the thin layer at the interface as can be seen from Fig. 11a. Some references [19-21] suggest that 850°C to 1200°C are suitable temperatures for diffusion occurrence. According to Trent [19], these temperatures are high enough to allow considerable diffusion to take place in the solid state condition.

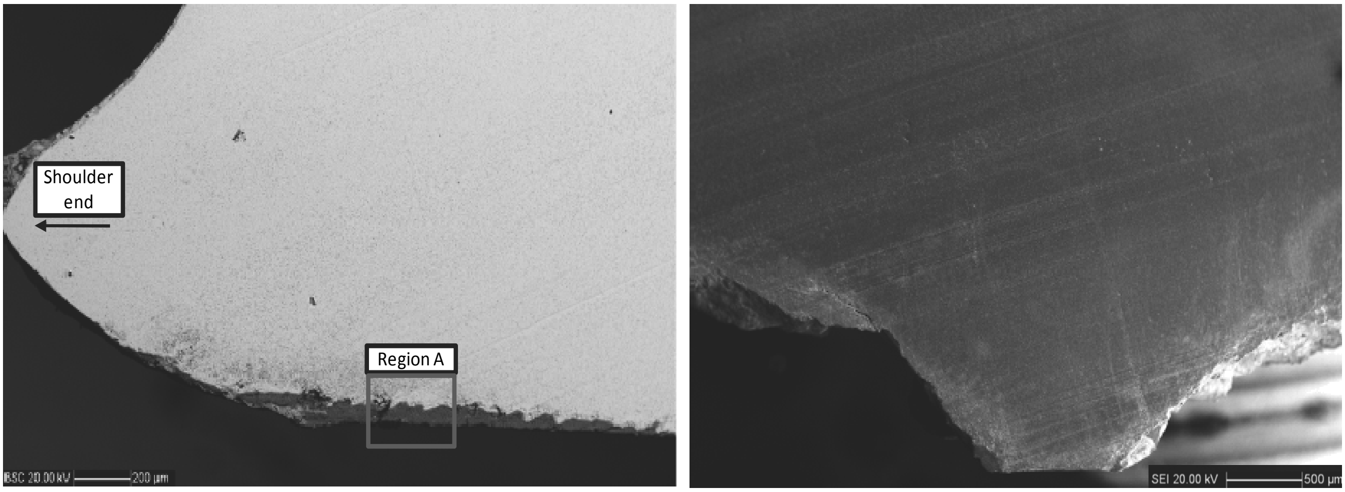
In the EDS mapping, Fig. 11b, characteristics are consistent with a process based on solid phase diffusion.

In Fig. 11a, veins of Co and W migrating to TiN can be observed, and in Fig. 9b, the mapping shows the diffusion "movement" of the Co and W atoms.



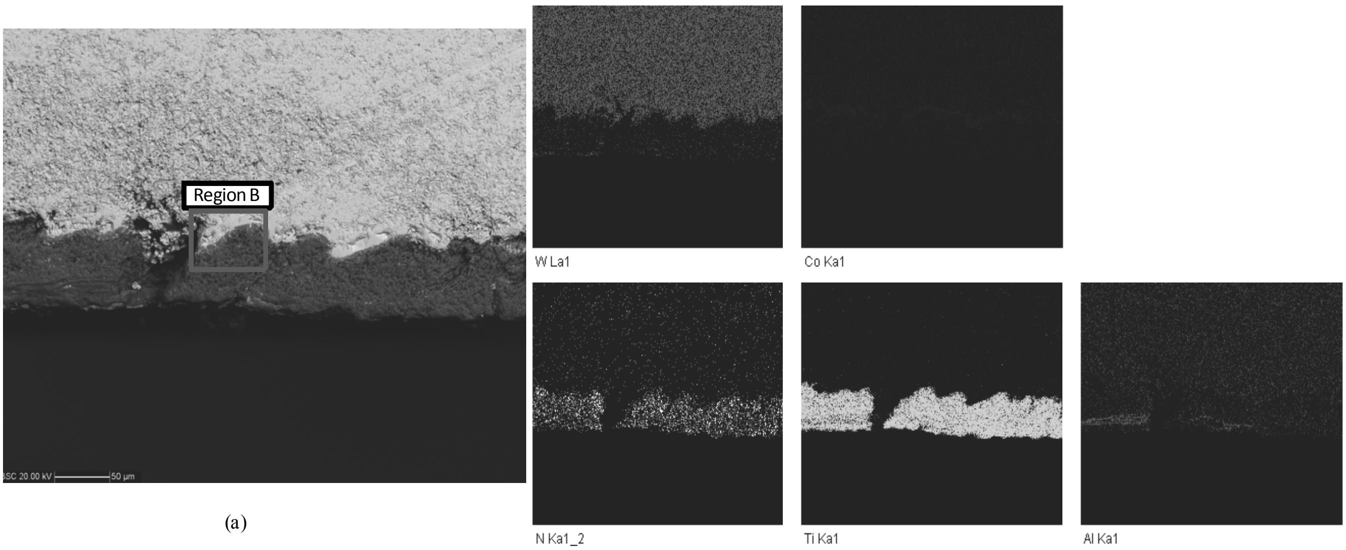
(a) (b)

Fig. 8. (a) Micrograph of tool shoulder showing; (b) EDX maps of tool shoulder showing the components found



(a) (b)

Fig. 9. (a) Transversal micrograph of tool shoulder; (b) transversal micrograph of tool pin showing the fractured region



(a) (b)

Fig. 10. (a) “Region A” - BSE micrograph showing severe deformation of the WC area, (b) mapping of “Region A” showing materials constituents, especially TiN

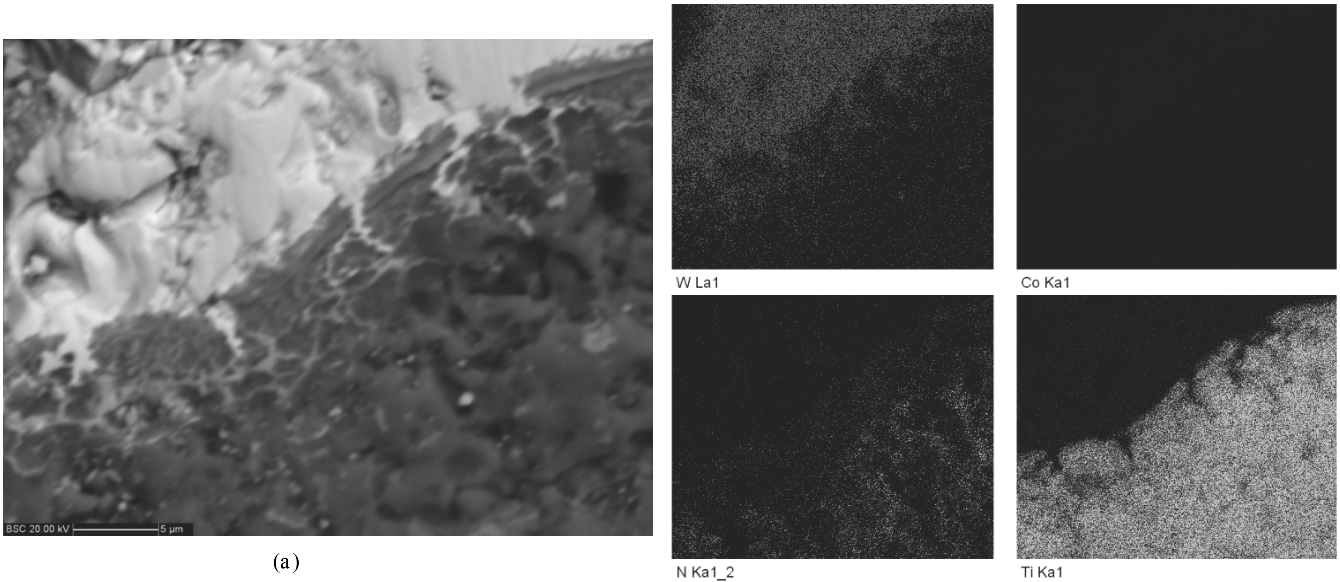
It worth observing that: W is not alone in the process but is instead combined with C that combines with Ti in covalent bonding, forming a precipitated phase TiC.

The atomic diffusion process of WC-Co FSW tool occurs first due to the tool Co atoms of the carbide bond and the Ti atoms from the sheet. Cobalt atoms form limit of the solid solution with Titanium which undergoes eutectoid transformation (a solid phase splits into two solid phases) and then lowers the transition temperature facilitating and accelerating the diffusion process.

Secondly and more slowly, W and C atoms due to Co atoms from the tool for its side are diffusing-out; thus, Ti atoms from the sheet workpiece diffuse-in provide support to the carbide grains, which in turn hinder their removal.

With WC tool material, carbide grains are not isolated and constitute the bulk of the material, therefore supporting each other in a rigid framework; C atoms being small, diffuse through the Ti matrix; however, those in the tool are strongly-bonded to W and are not free to move by themselves.

More details about possibilities of the FSW on the processing of light alloys like aluminum and titanium alloys regarding tool and workpiece materials combinations as well as experimental methodology can be seen at the reference [22-27].



(a) (b)

Fig. 11. (a) "Region B" - BSE micrograph showing diffusion mechanism, (b) mapping of "Region B" showing materials interface

5. Conclusions

A FSW processing on a titanium sheet was carried out with a tool made of a conventional WC coated tool coated with an (Al, Cr)N protective layer, which was supposed to improve wear resistance, lessen adhesion between the tool and the workpiece and act as a diffusion barrier.

For this preliminary study severe processing parameters were employed, i.e.: high tool rotation and no cooling environment to emphasize the wear mechanisms.

Despite being used in tool manufacture in which friction and temperature are high, the WC-Co tool had marked wear and the coating was totally eliminated during the FSW processing.

The tool degradation was evaluated by scanning electronic microscopy in order to observe the main tool wear mechanism.

The real contribution of the (Al, Cr)N coating layer could not be correctly evaluated, since there is no residual trace of its components at the worn tool. What was found left from the coating layer was the N component which formed the nitride TiN observed by EDS mapping.

The parameter conditions were probably too severe, overcoming the layer limit strength. A further analysis should be performed with more lenient parameters.

Strong adhesion from the workpiece material was found at the pin and shoulder which was responsible for the tool fragmentation; a second mechanism could be observed as the diffusion of the tool and the workpiece materials constituents.

As revealed from EBSC micrographs, at the tool/material interface, veins of Co and WC migrating to TiN layer by atomic diffusion process were observed.

The mechanism for the tool deformation took place solely by the action of high temperature and vertical pressure at the end of the tool which was in rotating and advancing process.

The deformations occurred from the tool center to the shoulder end, accordingly decreasing in intensity at the shoulder end region, where the temperature tends to be lower for being in contact with the environment.

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