Friction Stir Welding European Qualifications

CU10 – Designing of Tools

FSW Engineer

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10. Joint Definition

10.1 Good practices for FSW tools development

10.2 Characteristic of the tool material

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Introduction

- Welding tool is an inseparable component for welding by FSW process
- Welding tool serves for plasticizing and stirring of the material welded

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Welding Tool – Requirements

The following requirements are laid upon the welding tool:

- ✓ Simplest possible shape in order to reduce the costs
- ✓ Resistance against high temperatures
- ✓ Wear
- ✓ High fracture toughness
- ✓ Low thermal expansivity
- ✓ Good machineability
- ✓ Low price

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Welding Tool

- Welding tool is exposed to heavy loading and high temperatures, especially in the case of welding material with the melting point above 900°C (steels and titanium alloys).
- Commercial application of these alloys is limited by the price and short life of welding tools.
- Considerable progress in the field of welding steels by use of FSW process was attained in the last two decades.
- The manufacture of welding tool necessitates a proper selection of material, design of suitable shape geometry and the required heat treatment.

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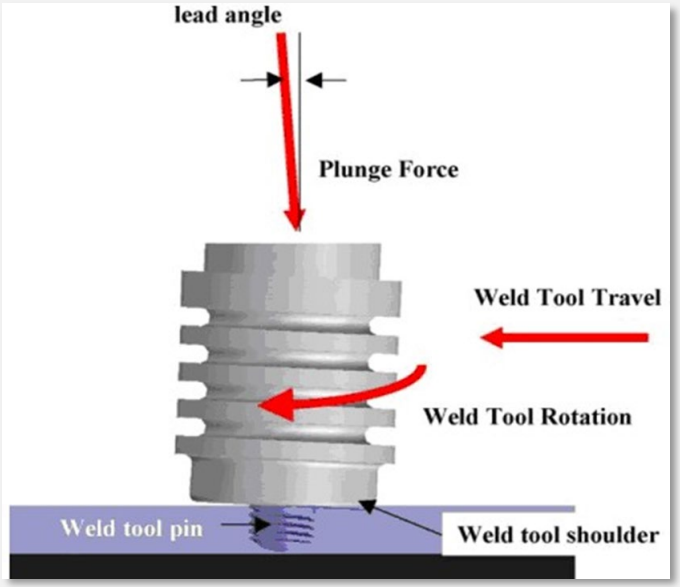
Welding Tool – Geometry

Welding tool can be divided into **two main parts**:

- ✓ Welding tool shoulder
- ✓ And pin (point) of the welding tool



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Welding Tool – Main Functions

- At contact of welding tool pin with welded material the heat, which is necessary for plasticizing of material welded is generated.
- The tool shoulder executes the pressing and forging function for the plasticized material.
- Welding tool serves for welded joint formation.
- The first TWI development design made in the field of welding of Al and its alloys, has employed the tool of concave cylindrical shape with a thread.
- The welding tools are usually made of tool steel.

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Welding Tool – Geometry

Geometry of welding tool affects:

- Rate of heat generation
- Downward force
- Torque
- Thermodynamically affection of material welded

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Welding Tool

The flow direction of plasticized material is affected by both, the welding tool geometry and also by the linear and rotary movement of welding tool.

Main parameters of welding tool:

- ✓ Shoulder diameter
- ✓ Angle of shoulder
- ✓ Pin geometry (including shape and size)

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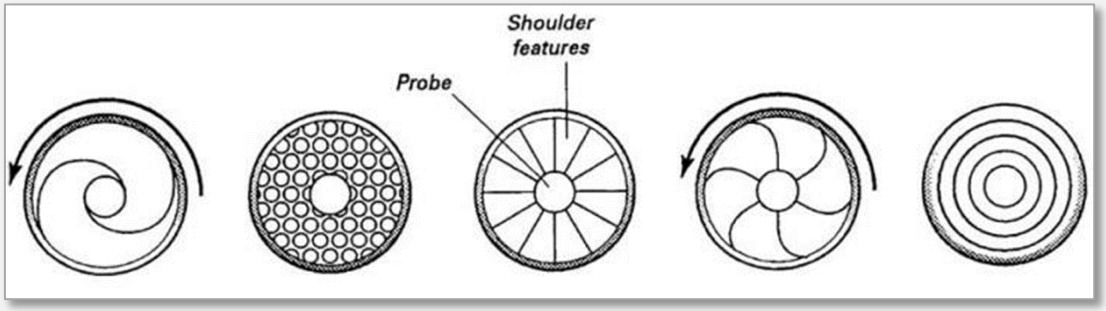
Welding Tool – Shoulder Geometry

- The tool shoulder serves for heat generation on the surface and in the surface vicinity of material welded.
- At heavier thicknesses of welded material, the heat generated by the tool shoulder does not exert such effect upon formation of a sound weld as the heat generated by the pin.
- The shoulder performs the forging and pressing function and forms the weld surface area
- The shoulder may be of different shapes:
  - ✓ Striae
  - ✓ Grooves
  - ✓ Concentric circles
  - ✓ Blades



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Welding Tool – Shoulder Geometry

- The **diameter** of welding tool shoulder is important, since the shoulder generates and maintains most of heat inevitable for plasticizing of material welded.
- Experimental studies have shown that the highest strength of welded joint can be achieved at **optimum diameter of welding tool shoulder**.
- The **microstructure of welded joint** may be significantly altered by replacing the tool shoulder of flat shape with a concave shape.
- The convex shoulder enhances the **stability of FSW process**. It results in reduced downward force and immersion depth of welding tool.
- Application of a **convex shape of welding tool shoulder** has proved minimum occurrence of excessive flash, when compared to the concave shape of shoulder.
- The **concave shoulder of welding tool** may result in a high thermal gradient and high surface temperatures during welding, what may lead to deteriorated quality of welded joint.

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Welding Tool – Tool Geometry

- The **tool pin**:
  - Causes the friction and material deformation on the weld joint
  - Is designed in such a manner to allow its easy penetration into the material to be welded
  - Affects the degree of deformation and stirring of material

- The **pin geometry** significantly affects the welding parameters:
  - ✓ Welding speed
  - ✓ Rotation speed of the tool
  - ✓ Downward force

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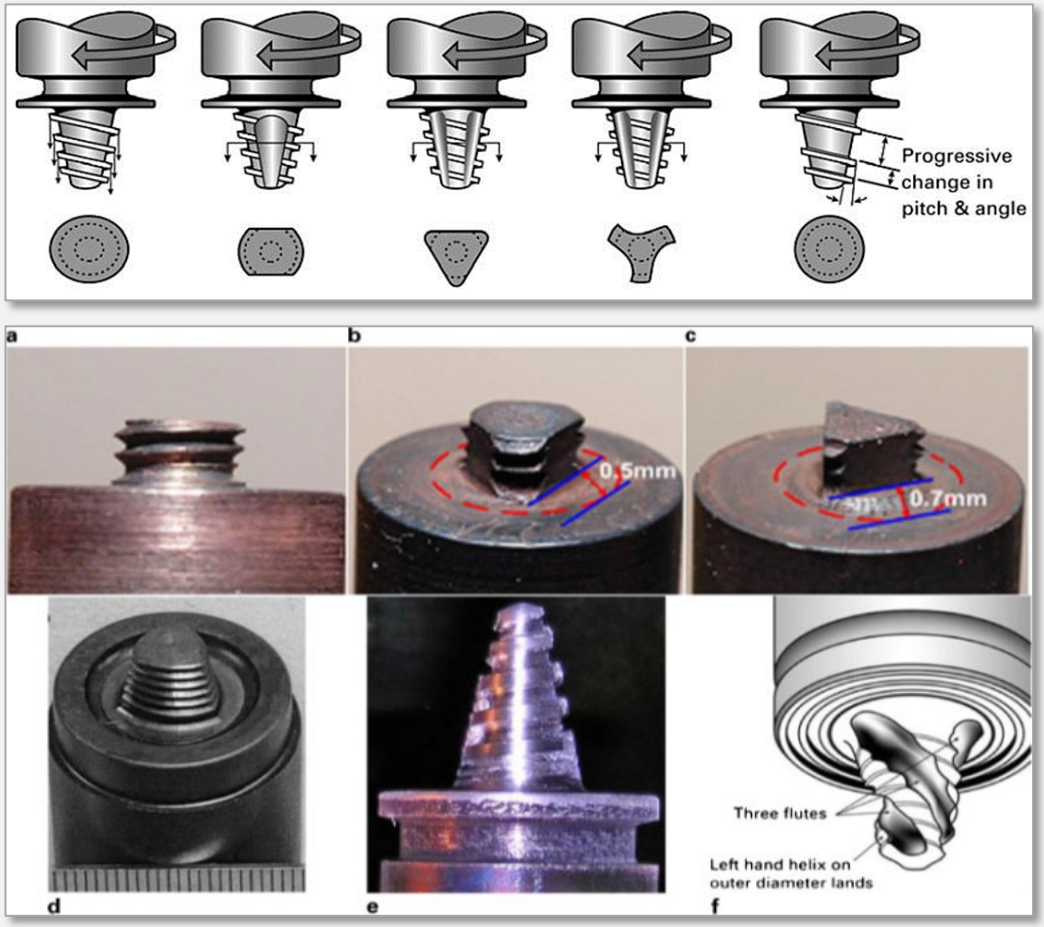
Welding Tool – Pin Geometry



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Welding Tool – Pin Geometry

- The rate of downward force and direction of material flow in welding tool vicinity are affected by the **orientation of threads on the pin surface**
- The threads and grooves on the pin enhance the rate of heat generation, owing to greater boundary area, improve the material flow and affect the axial and transverse forces
- Experimental welding has proved that the pin of **triangular shape** enhances the material flow, when compared to the pin of cylindrical shape.
- The triangular pin shape is advisable to employ for welding of **harder materials.**

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Characteristic of welding tool material

- The material of welding tool destined for welding materials with high melting point must exert good properties at the temperatures above 900 °C.
- Besides the demands on strength, fatigue resistance and toughness at elevated temperatures, the welding tool material must be resistant also to mechanical and chemical wear.
- Polycrystalline Cubic Boron Nitride (PCBN) and refractory metals are the mostly used materials, meeting the properties for welding tool manufacture.

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Recommendable materials for the welding tool

Alloys	Thickness [mm]	Weld tool materials
Mg	< 6	Tool Steel
Al	< 12	Tool Steel, MP 159
Cu	< 50	Alloys Ni, W, PCBN
Ti	< 6	W alloys
Stainless Steel	< 6	PCBN, W alloys
Low alloy steel	< 10	WC, PCBN
Ni	< 6	PCBN

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Characteristics of the Tool Material

- Each material of welding tool has the defined maximum temperature for which it may be applied.
- The excessive wear of welding tool causes the change in tool shape, what impairs also the weld quality and the probability of defects is thus increased.
- The tool wear may be caused by the adhesive, abrasive and chemical wear.
- The welding tool may be worn by the interaction mechanism between the welded material and tool material.

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Characteristics of the Tool Material

- In the case if the tool is made of PCBN material, the adhesive wear occurs at low tool revolutions, whereas at high tool revolutions the abrasive wear is observed.
- Oxidation may cause the change in material wear resistance.
- The tool reactivity may be suppressed by application of shielding gases supplied to welding process zone.
- The stresses formed at first tool contact with material welded may result in tool rupture.
- To prevent such a failure, mainly slow rate of pin penetration is efficient.

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Characteristics of the Tool Material

The **mostly used materials** for manufacture of welding tool can be classified to the following groups:

- ✓ PCBN, PCBN-WRe materials
- ✓ Refractory metals
- ✓ Light alloys
- ✓ Tool steels

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Characteristics of the Tool Material

The tools made of **PCBN material** are used for welding of alloys with high melting point:

- Austenitic stainless steel
- Duplex stainless steel
- Super martensitic stainless steel
- Ni alloys
- Tool steels

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Characteristics of the Tool Material

- A new grade of PCBN material was developed, using WRe as a binder.
- The PCBN-WRe grade of tool steels offers significantly improved toughness, compared to PCBN material proper.
- The austenitic stainless steels generally exert the highest rate of welding tool wear.
- Welding parameters play a significant role in the wear rate of welding tools.
- For the tool made of PCBN material, a rule stating that the temperature of welding tool should not exceed 900°C is applied.

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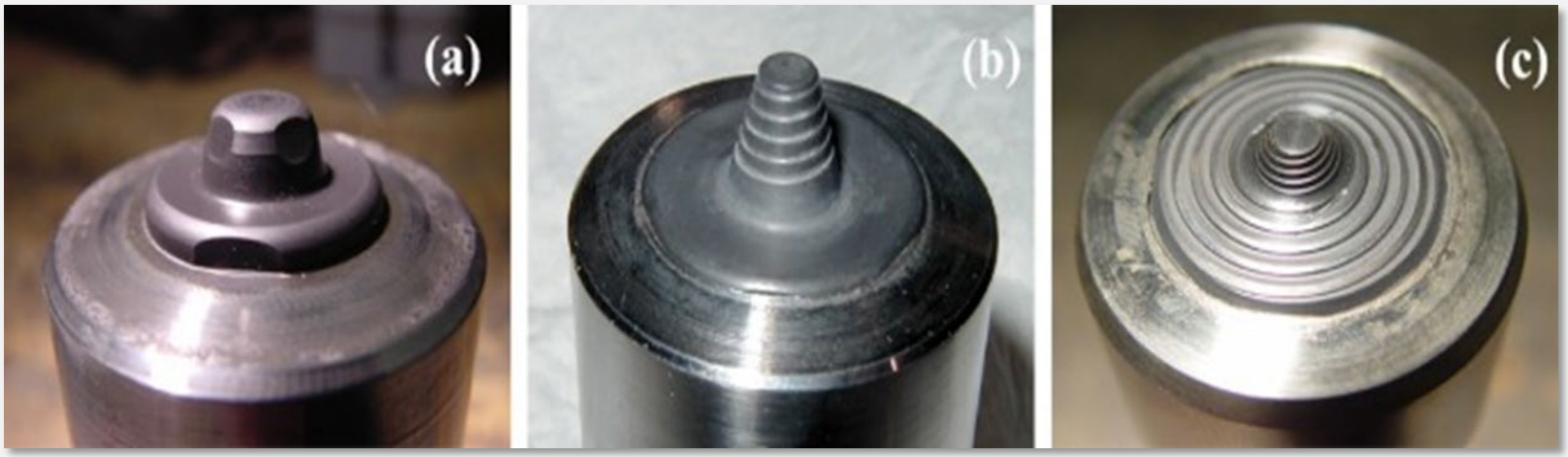
Characteristics of the Tool Material



PCBN tool design evolution:

(a) Early featureless design

(b) Step spiral probe

(c) Convex scrolled shoulder step spiral probe

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Characteristics of the Tool Material

- At the wear of functional parts on a welding tool made on the basis of PCBN-WRe material, these worn parts can be several times profiled what results in a prolonged life of welding tool.
- The high stresses formed during tool penetration, together with material fatigue at bend load during welding are the primary causes of welding tool rupture.
- In order to suppress the tendency to rupture, it is advisable to drill preliminary a hole in the point of supposed welding tool penetration.
- The best results with strength properties of PCBN material are achieved at the thickness up to 8 mm. At the thickness over 8 mm, better properties are achieved with the welding tools made of PCBN-WRe material.

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Tools of refractory metals

- The **Tungsten–Rhenium** alloy became a popular refractory material used for manufacture of welding tool destined for welding of steels.
- Addition of Rhenium element significantly improves the material strength at high temperatures.
- Rheniun reduced the pin deformation during penetration and it also reduced the wear of tool pin.
- In spite of that, the wear rate is still high. Therefore a simple shape of welding tool is preferably selected.

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Tools of refractory metals

- The shoulder and pin made of refractory material type WRe are smooth without the thread helix.
- Also small amounts of hafnium carbide (HfC) were added to refractory materials
- Another experiments were performed with the materials as: WC-Co, W-La, La_2O_3, Si_3N_4
- Though the quality of welded joints fabricated with the tool of the mentioned materials was acceptable, the tool life and costs have limited their application mostly for the research purposes

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Tools of light alloys

- The Ni and Co based alloys are used as the tool material for welding of steels.
- The tool made of Co-based alloy is used for welding high-carbon steels, which shows a good wear resistance.
- The welding tools made of light alloys are manufactured similarly as the tools made of refractory metals.
- The pin of welding tool is in the shape of a truncated cone.

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Tools of tools' steels

- The materials as Al, Mg alloys and composites of Al matrix are currently welded by the welding tool made of a tool steel.
- The welding tool made of a tool steel is used for welding of composite materials.
- The wear of welding tool at welding the metal matrixes of composites is greater, when compared to welding of soft alloys, owing to presence of hard abrasive particles in the composite materials.
- The experiments have proved that the welding tool which welded the composites of Al matrix was worn during welding and attained a new, own – optimised shape, after which the wear was significantly reduced.
- This shape depends on the process parameters and it can generally reduce the wear as in the case of initial tool shape, supposed that the integrity of welded joints is preserved.

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Tools of tools' steels

- The overall wear of welding tool increases with increasing rotation speed, while it is reduced with lower welding speed.
- The correct setting of welding parameters will result in lower wear of welding tool.
- Several studies have pointed out, that the welding tools do not need the pin geometry modified by a helix thread.
- High hardness, low coefficient of thermal expansion and high thermal conductivity make the Si_3N_4 material suitable for manufacture of welding tool.
- The coating of welding tool with an inert material as diamond or TiC, leads to a further improvement of wear at high temperatures.

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Wear, deformation and failure of the welding tool

- The welding tool is worn during welding (rotation and material stirring).
- The welding tool may be plastically deformed owing to reduced strength limit at elevated temperatures and load.
- If the loadings are higher than the load capacity of welding tool, a failure may occur.
- The main wear mechanisms include the adhesive, abrasive and chemical wear.

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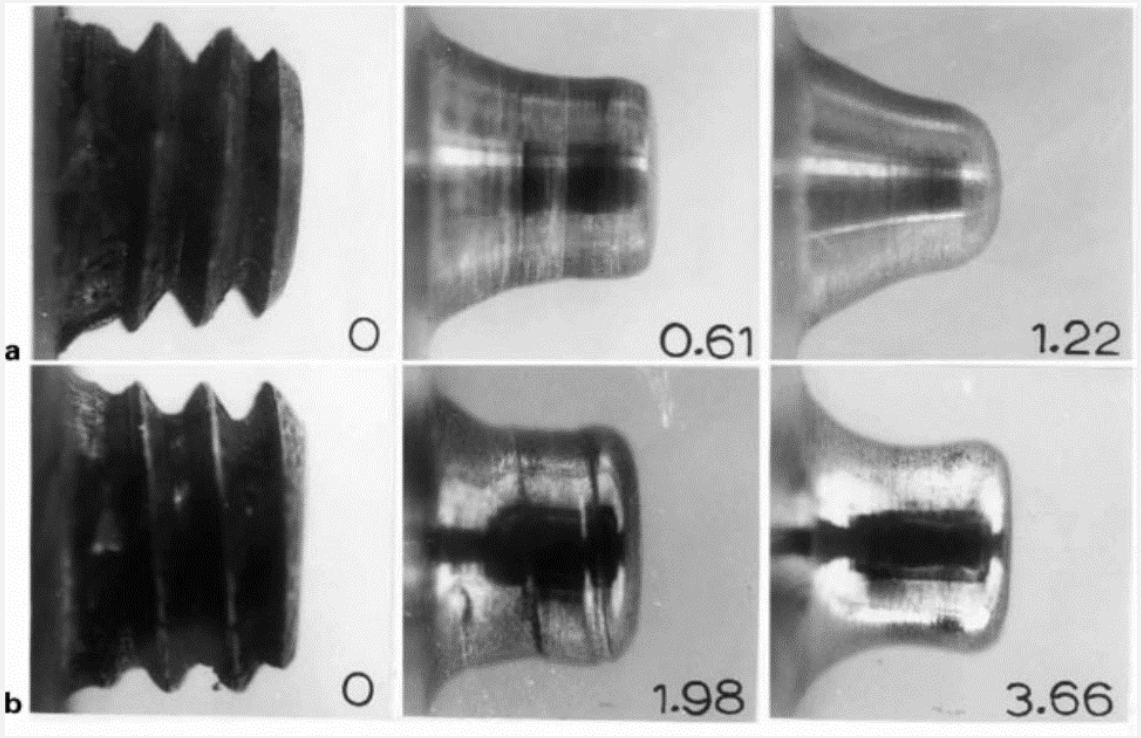
Wear, deformation and failure of the welding tool



Evolution of tool shape due to wear in FSW of Al 6061z20 vol.-%Al2O3 metal matrix composite

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Wear, deformation and failure of the welding tool

It was experimentally proved that:

- After **initial wearing out** of the thread on the point of a hard welding material, the wear rate has significantly reduced and, in spite of that, the smooth pins allow to fabricate sound welded joints.
- The high-strength materials as: PCBN and W are selected due to **reduced plastic strain** of welding tool.
- The high fracture toughness of welding tool material is essential in order to **reduce the probability of a rapid brittle fracture**.

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Wear, deformation and failure of the welding tool

When comparing the pin and shoulder of welding tool, almost always the wear and deformations in the pin section of the tool occur for the following reasons:

- The pin of welding tool is immersed into the welded material, where it must withstood greater resistance against its movement, compared to the shoulder, which is immersed into welded material just partially.
- The pin of welding tool has much lower load capacity that the shoulder.
- The high loadings combined with the torque and bend stresses lead to higher load exerted on the pin, compared to the shoulder of welding tool.

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Wear, deformation and failure of the welding tool

- The composite tools made of harder materials resistant to wear (PCBN, WC) for pin and relatively softer material (W-Re alloy) for the shoulder of welding tool may be the solution for issues regarding the tool life and reducing the costs for tool manufacture.
- In case of welding the overlapped joints of a harder and a softer material, the welding tool is situated into the softer material.
- The contact between the welding tool and harder material will be prevented, in order to reduce the wear of welding tool.
- Further research in the field of wear leads to experiments oriented to welding at slower welding speeds, preheating the material welded and application of shielding atmosphere.

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Costs for the tool

- The power costs in welding of Al alloys are considerably lower when compared to welding of steels. It is given mainly by the material price and mainly by the price for its processing.
- The PCBN material is often used for welding harder materials.
- The costs for production of welding tool made of PCBN material are high.
- The welding tools made of W-RE and W-La alloys are relatively cheaper than the tools made of PCBN, but regarding the wear, they exhibit faster wearing, owing to their lower strength and hardness at elevated temperature.
- Due to above mentioned reasons, it is necessary to invest to research for a further development of price more affordable and more reliable tool materials.

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Conclusions

- The FSW tool is subjected to heavy loading and high temperatures mainly in welding of hard alloys as steels and titanium alloys.
- Production of welding tool necessitates a proper material selection needed for its manufacture and design of a suitable geometry of the tool shape.
- Welding tool must meet the following requirements: the simplest shape in order to reduce the production costs, resistance against high temperatures, wear, high fracture toughness, low thermal expansivity, good machinability and low price.
- The welding tool is composed of two parts – the shoulder and pin.
- The tool shoulder executes the pressing and forging function for the plasticized material.

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Conclusions

- The tool pin causes the friction and deformations of material in the weld joint line.
- Beside the requirements on strength, fatigue and toughness at elevated temperatures, the material of welding tool must be resistant against the mechanical and chemical wear.
- Tool steel is used for manufacture of welding tool suitable for welding of Al and Mg alloys.
- The mostly used materials for manufacture of welding tools for welding of steels are: PCBN, WC, WRe, Ni and Co based alloys.
- The high-strength materials as: PCBN and W are selected owing to reduction of plastic deformation of welding tool.

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Conclusions

- The composite tools made of harder materials, resistant against the wear (PCBN, WC) for the pin and relatively softer material (the W-Re alloy) for the shoulder of welding tool may be the solution of issues regarding the tool life and reduction of manufacturing costs of the tool.
- Further research in the field of wear leads to experiments oriented to welding at slower welding speeds, preheating the material welded and application of shielding atmosphere.
- The power costs in welding of Al alloys are considerably lower when compared to welding of steels. It is given mainly by the material price and mainly by the price for its processing.
- Due to above mentioned reasons, it is necessary to invest to research for a further development of more affordable and more reliable tool materials.

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