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Book Title	Advances in Design, Simulation and Manufacturing IV	
Series Title		
Chapter Title	Structure and Properties of Surface Bandage Shelves for the Gas Turbine Engine's Blades	
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Author	Family Name	**Zaichuk**
	Particle	
	Given Name	**Natalia**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska Street, Lutsk, 43018, Ukraine
	Email	a.tkachuk@lntu.edu.ua
	ORCID	http://orcid.org/0000-0001-6258-4820
Author	Family Name	**Shymchuk**
	Particle	
	Given Name	**Sergii**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska Street, Lutsk, 43018, Ukraine
	Email	
	ORCID	http://orcid.org/0000-0002-1293-560X
Corresponding Author	Family Name	**Tkachuk**
	Particle	
	Given Name	**Anatolii**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska Street, Lutsk, 43018, Ukraine
	Email	
	ORCID	http://orcid.org/0000-0001-9085-7777
Author	Family Name	**Feshchuk**
	Particle	

	Given Name	**Yurii**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska Street, Lutsk, 43018, Ukraine
	Email	
	ORCID	http://orcid.org/0000-0001-6259-1916
Author	Family Name	**Szczot**
	Particle	
	Given Name	**Jacek**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Airport Lublin SA
	Address	6, Zesłańców Sybiru Street, 20008, Lublin, Poland
	Email	

Abstract	Analysis of the properties of the materials from which the parts of a gas turbine engine are made showed that they must have a high melting point, high strength, high creep resistance, and be machined. Therefore, the best option for strengthening the blades of titanium alloy VT3–1 is the formation in the wear zone of a thermodynamically compatible, heat-resistant, and wear-resistant layer, which is different from the main material of the blade. Samples for research were cut from the bandage shelves of the compressor blade in the shank area: the first - with high-quality soldering relite, the second – the shelf is worn, and there is a defect in the form of a drop. It was found that the main titanium alloy has a homogeneous structure, and the surface of the defective coating has a lower roughness, microcracks. Its local areas differ in elemental composition. Clusters of pores explain the clear and wide grain boundaries of titanium alloy under defective soldering at the boundaries. Such clusters of defects are etched more strongly than the base metal, so the base alloy has a needle-like martensite hardened structure formed by rapid cooling in the air after soldering. It is proved that such defects are formed due to the violation of soldering technology. It is proposed to create a protective layer of composite material VTN-1 with tungsten particles, which contains solid parts of tungsten carbide and titanium-based solder VPr16, to strengthen the working blades in the wearing zone.

Keywords (separated by '-')	Heat resistance - Soldering - Relit - Bandage shelf - Titanium alloy - Spectral analysis - Mechanical properties

Structure and Properties of Surface Bandage Shelves for the Gas Turbine Engine's Blades

Natalia Zaichuk[1], Sergii Shymchuk[1], Anatolii Tkachuk[1](✉), Yurii Feshchuk[1], and Jacek Szczot[2]

[1] Lutsk National Technical University, 75, Lvivska Street, Lutsk 43018, Ukraine
a.tkachuk@lntu.edu.ua
[2] Airport Lublin SA, 6, Zesłańców Sybiru Street, 20008 Lublin, Poland

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Abstract. Analysis of the properties of the materials from which the parts of a gas turbine engine are made showed that they must have a high melting point, high strength, high creep resistance, and be machined. Therefore, the best option for strengthening the blades of titanium alloy VT3–1 is the formation in the wear zone of a thermodynamically compatible, heat-resistant, and wear-resistant layer, which is different from the main material of the blade. Samples for research were cut from the bandage shelves of the compressor blade in the shank area: the first - with high-quality soldering relite, the second – the shelf is worn, and there is a defect in the form of a drop. It was found that the main titanium alloy has a homogeneous structure, and the surface of the defective coating has a lower roughness, microcracks. Its local areas differ in elemental composition. Clusters of pores explain the clear and wide grain boundaries of titanium alloy under defective soldering at the boundaries. Such clusters of defects are etched more strongly than the base metal, so the base alloy has a needle-like martensite hardened structure formed by rapid cooling in the air after soldering. It is proved that such defects are formed due to the violation of soldering technology. It is proposed to create a protective layer of composite material VTN-1 with tungsten particles, which contains solid parts of tungsten carbide and titanium-based solder VPr16, to strengthen the working blades in the wearing zone.

Keywords: Heat resistance · Soldering · Relit · Bandage shelf · Titanium alloy · Spectral analysis · Mechanical properties

1 Introduction

The basis of modern aircraft construction is a gas turbine engine (GTE). GTE blades are the most numerous parts. Their total number in the engine is about 3000 pieces. The reliability of gas turbine engines depends on the compressor and turbine blades' reliability, as they are the most loaded parts [1]. They are located in the gas stream and in the area of high temperatures, are designed to change the parameters of the engine and consist of a root or shank (Fig. 1, a), which serves to attach the blades in the housing, the working part - the blade washer and the top in the form of a spike on which the bandage tape connecting shovels is put on [2].

V. Ivanov et al. (Eds.): DSMIE 2021, LNME, pp. 1–11, 2021.
https://doi.org/10.1007/978-3-030-77719-7_60

The gas turbine engine's blades work in the conditions of multiple heat changes, are exposed to high-temperature gas flows, and experience additional fuel components and products of its combustion [1, 3]. This effect causes high-temperature salt corrosion, which is a process of rapid oxidation and sulfidation of the blade's working surface under the influence of combustion products with high sulfur fuel and determines the service life of the aircraft. The study of the structure and surface properties of titanium alloy VT3–1 without soldering and with soldering of wear-resistant material will determine the best combination of mechanical, physical, and technological properties necessary to increase the wear resistance of the surface of the bandage shelves and increase the service life of the blade [4].

2 Literature Review

Turbine blades are widely used in modern gas turbine engines. The use of bandage shelves reduces alternating voltages from vibration loads and thus increases the gas turbine engine's overall service life and reliability [5]. However, in the operation of the working and nozzle blades resulting from significant contact stresses under conditions of friction and vibration at the contact points of the shelves, there is increased wear of the contact surfaces compared with the pen and the blade lock [6]. Ensuring parameter identification [7] for rising operating temperatures and aircraft engines' service life sharply intensifies the processes that lead to damage and destruction of the blades' contact surfaces, limiting their service life and reliability [8, 9].

In general, the following defects may occur during the operation of the blades:

- cracks in the main metal and surface cracking due to fatigue wear [10];
- damage to the surface layers of parts due to corrosion [11–13];
- increased operation of contact surfaces under the conditions of friction [14] and vibrations [15].

Despite all their advantages, Titanium alloys have low wear characteristics, which leads to the need to address the issues of increasing the service life of parts made of these materials and the problems of strengthening and repairing worn surfaces. This primarily applies to the contact surfaces of the bandage shelves of the blades of the compressor GTE. From the experience of aircraft repair units, it is known that one of the most profitable and effective ways to repair many engine parts is welding [4, 14]. However, the results of studies of the mechanism of wear of contact surfaces allow concluding that the best option to strengthen the blades is to create in the wear zone a layer of highly heat-resistant and wear-resistant material, different from the blade's material [2, 8, 16].

3 Research Methodology

Titanium alloys do not have entirely satisfactory tribotechnical properties, for most compressor blades of aircraft engines use the alloy VT3–1, which satisfies the performance characteristics, and its use is economically justified. Repair and restoration of these parts allow to extend service life and to reduce expenses at regular maintenance. Surfacing on the blades of the wear-resistant and heat-resistant layer of VTN-1 alloy was performed by the vacuum-arc method.

The surface analysis of samples made of titanium alloy VT3–1 was performed. The sample's surface was studied using a REMMA electron microscope, a high-resolution scanning electron microscope, and an X-ray microanalyzer. The samples were cut from different parts of the compressor blade's bandage shelves (Fig. 1, a). The study's object was: samples cut from the bandage shelves on which the relite was qualitatively applied (Fig. 1, b) and one – from the shelf, which contained a defect in the form of a drop (Fig. 1, c). Samples from the scapula feather that are not subject to intensive wear were also examined.

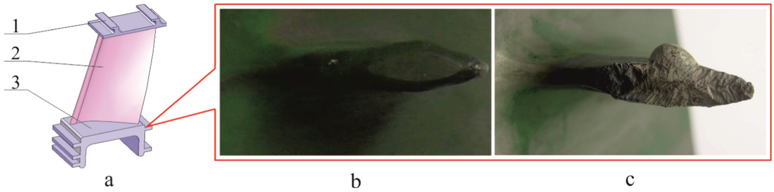


Fig. 1. The research object: a – the scheme of a shovel: 1 – shank; 2 - nib; 3 – top of the scapula with banding tape; b – high-quality soldering of wear-resistant material; c – soldering with a defect in the form of a drop.

Samples for research were cut from the bandage shelves after their operation and after soldering the relite. The samples' elemental composition was determined by X-ray microanalysis and electron microscopy [17, 18].

Investigations of mechanical properties were performed on the multifunctional "Micron-gamma" device by automatic registration during loading P on the indenter and the depth h of its immersion in the surface of the test material in the form of a load diagram $P = f\ (h)$.

4 Results

In particular, in this work, we studied the surface of samples made of titanium alloy VT3–1, cut from different parts of the compressor blade (Fig. 2).

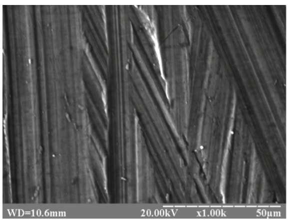
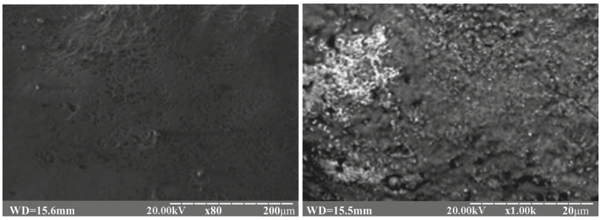


Fig. 2. Image of the section of titanium alloy VT3–1.

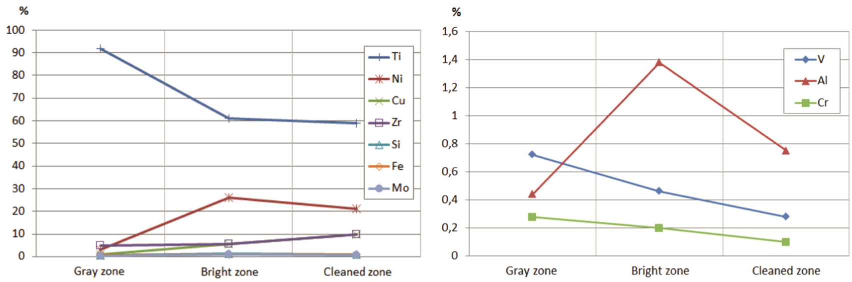
As a result of studies of the cut surface of the titanium alloy VT3–1, it was found that the alloy has a generally homogeneous structure (Fig. 3).



a b

Fig. 3. The image of the samples' surfaces with soldering: a - quality soldering, b - defective area.

There are also areas in the form of small inclusions. The surface structure indicates that the material is viscous and ductile, difficult to cut, and prone to sticking. The local analysis results indicate the homogeneity of the sample's chemical composition and its compliance with the chemical composition of VT3–1. Spectral analysis performed on soldering (Fig. 4) shows a homogeneous distribution of chemical elements on the sample's surface.



a b

Fig. 4. Comparison of the chemical composition of different parts of the defective sample.

The defective coating surface is characterized by a slightly lower roughness than high-quality soldering, and there are sometimes small cracks (which do not pass the thickness of the coating). Local analysis of the plots shows that they differ in elemental composition. In (Fig. 4, a) shows a graph of changes in the content of chemical elements depending on the area where the study was conducted; Fig. 4, b shows Al, Cr, and V.

Heterogeneity of the chemical composition could arise due to a violation of the technological process of soldering. As a result, the shelf is unusable due to the presence in areas of very high Ti content with low thermal conductivity, prone to sticking and bulging.

Comparing the average values of the quantitative composition of qualitative soldering, defective area, and base material is shown in Table 1, graphical representation of the content of elements is presented in (Fig. 5). In (Fig. 5, b) the lower part (Fig. 5, a) – elements Mo, Fe, Si, V, the content of which does not exceed 2.4%).

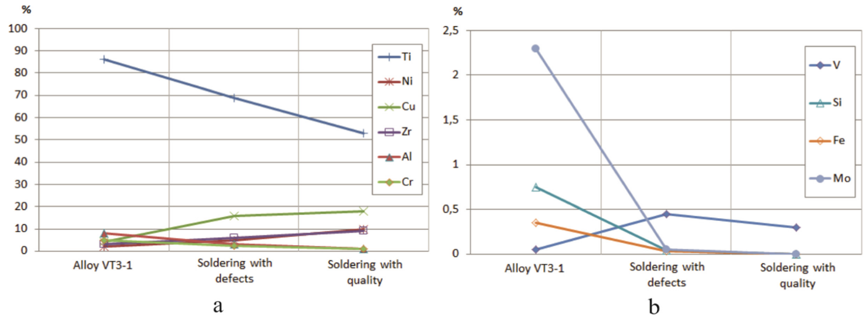


Fig. 5. Comparison of the chemical composition of different samples.

Table 1. Comparison of quantitative analysis of the elements of the base and soldering (accelerating voltage 20 kV).

Zone	The average content of elements, % (Σ = 100)									
	Al	Si	Ti	V	Cr	Fe	Mo	Ni	Cu	Zr
Quality soldering	0.52	–	51.7	0.29	11.72	–	–	10.85	16.47	8.97
Defective soldering	0.47	–	90.94	0.68	0.29	–	–	0.42	2.09	5.11
The base of the blade	8.09	0.77	86.71	–	0.75	0.34	2.34	–	–	–

It is possible to note that compared with a basis, the qualitative soldering contains the lowered quantity of Ti, Al, and the increased content of Cu, Ni, Zr. The defective area is characterized by an intermediate Ti content between the quality solder and the base. The content of Al, Cu, Zr, and V is close to its content in the quality solder.

All alloying elements increase the strength and reduce the ductility of titanium. Cu increases the stability during operation, increases the heat resistance of the alloy. Ni increases the strength and corrosion resistance of the coating. Zr increases the strength, heat resistance, and creep resistance of the coating at elevated temperatures.

Spectral analysis of the solders' chemical composition revealed elements present in the solder VPr16 (Cr, Ni, Cu, Zr). Still, it did not reveal the presence on the surface of the reinforcing phase - relit (W and C). This can be explained by the fact that the relay particles have a density 2.5 times higher than the solder's density, and in the process of soldering, they settle and, as a result, enrich the lower layers of the coating and deplete the upper ones. The studied samples' structure is primarily homogeneous, although in some areas, there is some inhomogeneity: local clusters of alloying elements or small pore size. They occur during the manufacture of the blade by injection molding when the cooling rate is significant, and the cross-section of the blade is small, gas or air bubbles do not have time to come to the surface. These structural defects are insignificant and do not affect the performance of the product. The structure of the initial alloy VT3–1 of the shoulder blades of the blade at the soldering point of the relit is significantly different from the structure of the pen and shank, which were not heated. On the etched section, the traces left after polishing are visible. This occurs since titanium alloy is a relatively soft material. They arise as a result of the hit of particles of a relit in a grinding zone. In such cases, it is recommended to use electrolytic polishing, which prevents defects of this type.

The microstructure of the solder also shows large grains with clear boundaries. Such grains are formed during microwave heating, and aging in soldering relit because the tendency of titanium to rapid grain growth at high temperatures is known. The presence of clear, wide grain boundaries of VT3-1 alloy under defective soldering is explained by the accumulation of pores and other defects at the boundaries such accumulations of defects are etched more strongly than the base metal. The alloy has a needle-like martensitic hardened structure formed due to rapid cooling in the air after soldering. Comparing the transition zones between quality soldering and base metal, and between defective soldering and base alloy, it should be noted that quality soldering has an equal gradual defect-free transition. While the boundary between defective soldering and the base metal is uneven, it is characterized by defects (pores, cracks). The microstructure of relite soldering is two-phase: light large WC crystals and etched dark areas of VPr16 solder. Light grains are very hard. The fine-grained equilibrium structure of the solder is less hard but more viscous, i.e., astringent.

In the soldering process, there are no phase reactions that radically change the reinforcing parts' composition and structure. Therefore, in the structure of the soldered layer, the relit particles, which provide high resistance to wear of the coating, should be evenly distributed and connected between themselves and the base material by solder. However, defective soldering has a heterogeneous structure: large, unevenly distributed relite grains, surrounded by an increased amount of solder. It has a fine-grained structure consisting of a β-phase. Relite grains, in contrast to solder, were not pickled because digestion was performed with a Kroll reagent designed to determine the structure of titanium alloys. Only traces of corrosion are observed on the relite grains.

In some areas of defective soldering, the coating is loose – you can see the area's presence with the structure of the main alloy of the blade VT3-1. Also, gas pores in this area have significant dimensions (up to 1 mm), smooth, smooth walls, and edges. High-quality soldering on the test sample is characterized by a uniform distribution of relit and a sufficient amount of solder. It covers the test sample's entire surface and forms a dense, high-quality defect-free coating that provides high hardness and strength during the blade's operation. An essential feature of the coating formation is the distribution of the reinforcing parts of the rafters in height. Tungsten carbide has a density 2.5 times higher than the solder's density, and in the process of soldering, it settles and, as a consequence, the enrichment of the lower layers of the coating and the depletion of the upper. The depleted upper layer is most clearly manifested by increasing the solder content in the paste and increasing the thickness of the soldered layer. Relite particles can also settle under forces arising from the electromagnetic stirring of the liquid solder bath during induction heating by high-frequency currents. Practically on the thickness of the soldered layer 0.2–0.3 mm from the strengthened surface of the reinforcing parts has almost uniform character.

The contact action research and control of materials' physical and mechanical properties in the near-surface layers are. Contact deformation is associated with almost all modern methods of processing, strengthening, and joining materials (metal processing by pressure and cutting, grinding, polishing) and service properties of materials in the conditions of friction, fatigue, setting, wear. The study presents the results of reduced and non-reduced microhardness. The Martens method was used to determine the restored hardness, and the Meyer method was used to determine the non-reduced hardness. It should be noted that the Meyer microhardness is equal to the average pressure in the impression and quantitatively accurately expresses the physical essence of hardness. The standard microhardness (in this case, according to Martens) is less than the Meyer hardness as many times as the area of the impression surface calculated for the indenter of the accepted geometry is greater than the area of the projection of the impression. After conducting the research, the computer program using the "Micron-gamma" device displayed on the monitor the values of strength in tables for each of the samples.

Analyzing the data for these samples, we can say that the highest value of unrecovered microhardness has relite grains (21.02 GPa). They provided the overall increase in surface microhardness with quality soldering relite (average 5.51 GPa). Under the same loading conditions, the unrestored hardness for other samples became slightly lower: for the sample with defective soldering 4.76 GPa, and the sample from the alloy VT3-1 approached 4 GPa (Table 2).

Table 2. Average values of microhardness of the studied surfaces.

The investigated surface	Restored microhardness Hμ, GPa	Unrestored microhardness Hμ, GPa
The surface of the sample from the alloy VT3-1	3.53	3.99
The surface of the sample with defective relite soldering	4.16	4.76
The surface of the sample with high-quality relite soldering	4.83	5.51
Relite grains	17.14	19.36

In (Fig. 6) shows histograms comparing the obtained average values of microhardness of the samples.

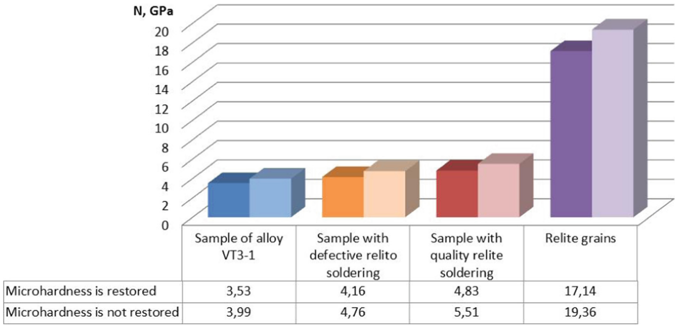


Fig. 6. Histogram comparing the average values of restored and unrestored microhardness of the studied samples.

A characteristic feature of titanium alloys is the low modulus of elasticity, which decreases with increasing temperature. Relite soldering allowed to increase this characteristic (Table 3), which will increase the part's rigidity and efficiency. Strength is one of the essential properties of the material. The tensile strength (σ_B), i.e., the maximum stress that can withstand the material when tested in titanium alloys, is quite high (Table 3), but in terms of wear, it is insufficient. Relite soldering provides an increase in the value of strength.

Table 3. Average values of mechanical properties of the studied samples.

The investigated surface	Young's modulus E, GPa	Plasticity index K	Tensile strength σ_B, GPa
The surface of the sample from the alloy VT3-1	133.46	0.78	0.879
The surface of the sample with defective relite soldering	132.80	0.76	1.022
The surface of the sample with high-quality relite soldering	136.22	0.75	1.151
Relite grains	178.67	–	1.532

In (Fig. 7, a) shows that the highest modulus of elasticity has a pattern with high-quality soldering, which is undoubtedly achieved by forming a high-quality coating and uniform grain distribution of the relay, which has a much higher Young's modulus. The lowest modulus of elasticity has a pattern with defective soldering, which could occur due to non-compliance with soldering technology. Analyzing the histograms comparing the ductility (Fig. 7, b), we can say that one of the reasons for the low wear resistance of titanium alloys is high ductility. Relite soldering reduces ductility, providing increased hardness, strength, and durability.

Comparisons of the average values of the modulus of elasticity, ductility, and tensile strength are presented in (Fig. 5), (Fig. 6), (Fig. 7).

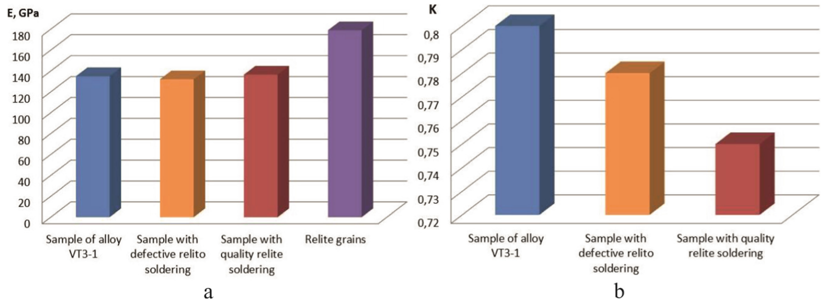


Fig. 7. Histogram comparing Young's modulus's average values (a) the average values plasticity of the studied samples (b).

Relite grains have high strength values (Fig. 7). They significantly increase the studied samples' tensile strength (by 30.9% compared to the sample of alloy VT3-1).

Examination of the samples revealed relit grains' presence, although a significant increase in mechanical properties is provided by relit powder, which is evenly distributed in the solder. Relite particles have a density 2.5 times higher than the solder's density. In the process of soldering, they settle and, as a consequence, the enrichment of the lower layers of the coating and the depletion of the upper ones. Reducing the content of relit in the upper layers of the coating has a positive value. It facilitates the machining of the soldered surface by decreasing the hardness of the upper layer.

5 Conclusions

The recommended option for strengthening the blades is to create a layer of heat-resistant and wear-resistant material VTN-1 in the wear zone, consisting of solid parts of tungsten carbide (relit) titanium-based solder VPr16 as a binder. Microstructural studies have shown that there have been no significant changes in the base alloy structure over the entire blade volume, although, in the alloy on the shelf shelves, grain growth and the formation of a martensitic needle structure occurred at the soldering point.

Physicomechanical parameters of samples from VT3-1 alloy and samples with defective and high-quality relite soldering showed a significant increase in mechanical properties of the sample with high-quality soldering in comparison with the sample from VT3-1 alloy: modulus of elasticity E by 2.1%, strength limit σ_B on 30.9%, unrecovered microhardness by 38.1%. The sample acquires such properties due to the high mechanical properties of the relite grains ($H\mu = 19.36$ GPa, $E = 178.67$ GPa, $\sigma_B = 1.532$ GPa) and the solder, which provides a strong connection of the relit grains with each other and with the main alloy.

The next stage of the study will be to determine the wear resistance and service life of the surfaces of the bandage shelves of the GTE blades, considering the above recommendations.

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Chapter 60

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Insert comma	(As above)	
Insert single quotation marks	(As above)	or and/or or
Insert double quotation marks	(As above)	or and/or or
Insert hyphen	(As above)	
Start new paragraph		
No new paragraph		
Transpose		
Close up	linking characters	
Insert or substitute space between characters or words	through character or where required	
Reduce space between characters or words	between characters or words affected	