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VALIDATION OF AN EXPERIMENTAL METHOD FOR PEAK TEMPERATURES EVALUATION ON A RR MERLIN XX HEAD

Luca Piancastelli[1], Federico Calzini[2] and Stefano Cassani[2]
[1]Department of Industrial Engineering, Alma Mater Studiorum University of Bologna, Viale Risorgimento, Bologna, Italy
[2]MultiProjecta, Via Casola Canina, Imola (BO), Italy
E-Mail: luca.piancastelli@unibo.it

ABSTRACT

Aluminum alloy properties are hugely influenced by temperatures and stress gradients. In piston engines, temperatures vary slowly when compared to operating pressure and stress. Therefore, averaging the temperature values is a valid assumption. This paper compares the experimental head temperatures of a Rolls-Royce-Merlin-XX-head with the ones of a NACA paper on a very similar Merlin-Packard-V-1650-7. This experimental method in based on residual hardness measurement on a head of a RR Merlin that crashed in Italy during WWII. The first part is to define the "working life" in hours of the engine. A few samples from a "cool" part of the head give the initial "thermally intact" hardness. Then the hardness of a few samples from a known temperature part is measured. In our case, it is the part of the head that is directly exposed to coolant. The time interval that gives a residual hardness equal to the one of the part of the head that is directly exposed to coolant gives the engine working life. For this purpose, a set of "cool part" samples are kept in at the maximum constant temperature of the coolant (135 degrees C). Then, a few specimens are kept at higher temperatures and are extracted from the oven at regular time intervals. The residual hardness is measured on these specimens. A further set of specimens is subjected to random thermal cycling to verify that the alloy hardness reduction is influenced by the time at high temperature and not by the thermal cycle history. In this way, a correlation between residual hardness and temperature is obtained for the specific engine alloy. It is then possible to measure the residual hardness of various points of the head and to obtain the maximum temperature reached in a specific point. In general, experimental tests have confirmed the cost-effectiveness of this approach. The NACA TM 2069 data and the ones measured with this method show an extremely good correlation. It is then possible to affirm that, also for the alloy used for the Merlin head, a modified Hiduminium RR50, this method of test is valid. Other positive tests were performed in the past with the much more common AlSi9 alloy used for the head of FIAT-1900jtd-8V automotive engine. The method of the residual hardness is old and has met several critics in the scientific community. This paper demonstrates that, for at least a few aluminum alloys, it is still valid. It is a very inexpensive method to evaluate temperatures in new engines using disposed units with a known load history and time. The results are precious to verify that the simulation results used in the head design led to reasonable results. In this way, the development time of new engines can be significantly reduced.

Keywords: temperature, measurement, piston engine, head, RR Merlin.

INTRODUCTION

Thermal field adds a significant amount of stress on the head at full load. In addition, the temperature distribution does affect significantly the cylinder filling and the combustion gas temperatures even in high-rpm engines. High wall temperatures penalize engine volumetric efficiency and knocking resistance. In fact, high temperatures not only reduce the density of the intake charge, but also decrease the fraction of heat dissipated by the fresh air. In addition, high walls temperatures are dangerous for the engine reliability. On the contrary, high temperature increases the thermodynamic efficiency of the cycle by improving the reference "Carnot" maximum temperature. However, this improvement is not sufficient to compensate the power reduction due to decreased air mass flow. In naturally aspirated engines, an intake-duct-wall temperature of 30% reduces the output power of 8%. In addition, lubricant capability and durability are highly affected by temperature. Finally, aluminum alloy strength has a 50% drop with an increase of temperature from 470K to 570K. Usually, design simulations on head temperature stress are limited to the full-load maximum-temperature condition due to high cost in term of human and computational time required by a proper head analysis. This is due to several factors linked to the complex geometry that varies with the piston position during the cycle. The gas temperature affects the heat exchange, the Mach and the Reynold number. Load related temperatures vary in seconds while pressure related stresses vary in milliseconds for variation of gas-dynamic conditions during the cycle. Long terms (load) variations largely affect the temperature field of the engine parts, while short terms variations (thermodynamic cycle) are averaged. For this reason, it is important to know maximum average temperatures in order to evaluate highly stressed parts behavior. In fact, exposure to temperatures above the specified ageing temperature has deleterious effects on the mechanical properties. The extent of damage caused by excessive heating is primarily dictated by the exposure time experienced by the affected surface. In the past, hardness tests had been generally used to estimate residual strength properties of aluminum-alloy engine components affected by thermal stress. In fact, maximum temperature reached is achieved by measuring the relative changes in hardness of affected areas and comparing them with reference values measured at cooled areas. However, relevant data on thermal damage are not limited to the specific conditions of the combustion chamber. Consequently, a test program that covers a wide range of temperatures should be set up to quantify the effects of thermal damage on the strength properties of engine alloys. The complexity of the head design may lead to large errors even for expert designers with many years of experience. This fact is aggravated by the common use of simplified alternative methods that reduce the simulation and the design time by at least an order of magnitude. The possibility to have an immediate an inexpensive feedback on temperature field after a few hours run on the brake is therefore precious. The test program described in this paper uses hardness as a mean to quantify the residual strength properties of the alloys at the working temperature. This is possible from temperature and residual-hardness correlation. This method is valid not only for the Merlin aluminum alloy but also for many aluminum-silicon alloys used in current automotive production. In addition, the insensitivity of the alloy to the temperature history can be easily and cheaply verified.

Figure-1. The Mosquito port RR Merlin XX engine at the beginning of the disassembly in Forli Laboratory of the Università degli Studi di Bologna - Italy.

HISTORICAL NOTES

Carlo Bezziccheri took the engine to the Forli Laboratory in 2006 (Figure-1). Afterwards it was disassembled, examined and restored by Mauro Ricci, Ivano Amadori and Andrea Burnelli. Ing. Andrea Burnelli, then a Master Student, made all the laboratory tests and measurements. The Historian Giuseppe Macina gave all the available information about the Mosquito crash which, sadly, took the life of D.H. Bentley (pilot) and V.H. Causeway (navigator) on 1943-11-20 00:26 ZT in San Marino (Italy). The engine seems to have been fully operational at the moment of the crash. The Authors wish to thank Andrea Burnelli, Giuseppe Macina, Carlo Bezziccheri, Mauro Ricci and Ivano Amadori for their essential contribution to the work necessary to arrive to the results shown in this paper.

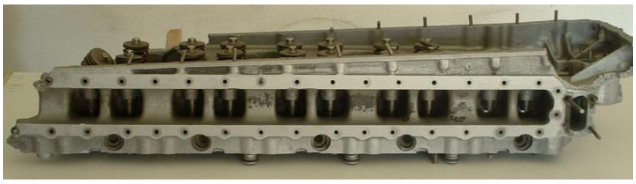

Figure-2. The head "A" after disassembly and cleaning (air intake side).

MATERIAL OF THE HEAD CAST

One of the engine heads (the most damaged one, head A, Figure-2) was restored and, with great care, sectioned in the most damaged parts to obtain very small test specimens. The head A is on the right side of the engine when seen from the supercharger. The metallurgical analysis result is shown in Table-1 (average values on 16 specimens from various head parts).

Table-1. Metallurgical analysis of head cast

Si %	**Fe %**	**Cu %**	**Mn %**	**Mg %**
3.05	1.10	1.72	0.06	0.01
Cr %	Pb %	Sn %	Ti %	Ag %
0.009	0.0290	0.0231	0.186	<0.001
B %	Be %	Ca %	Na %	P %
<0.0010	<0.0010	0.0050	0.0062	0.0018
Sb %	Sr %	Li %	V %	Zr %
0.0152	0.0004	0.0020	0.0076	0.006
Cd %	Co %	Zn %	Ni %	Al %
0.0044	0.004	0.063	0.75	92.87

Table-2. Mechanical properties of Hiduminium alloys 50 and 53 [1] [2].

	RR50 sand	**RR50 die**	**RR53 sand**	**RR53 die**
Tensile strength [MPa]	170 to 200	200 to 247	278 to 308	324 to 355
±Fatigue limit $2x10^7$ [MPa]	±69	±89	±84	±106
Elastic Modulus [GPa]	68.9 to 72.3		68.9 to 72.3	
HRB	65 to 75	70 to 80	124 to 148	124 to 148

This 3% silicon aluminum alloy is, with any probability, a derivative of the famous "Hi-du-minium (High Duty Aluminium) R.R. 50" aluminum alloy. From the documentation available, Hiduminium RR50 had Cu 0.8-2, Fe 0.8-1.4, Mg 0.05-2, Ni 0.8-1.7, Si 1.5-2.8, Ti 0.2. RR50 is specific for sand cast [1] (Table-1). However, it can be also a derivation of the Hiduminium RR53, which is more specific for die cast (chill cast). The formulation of this alloy is richer in copper with Cu 1.5-2.5 and slightly poorer in Si (0.2max). The performances of these two alloys are very different (Table-2 [1]). On average, the tests have provided a maximum hardness value equal to 83 HRB.Just to find an improper similarity with modern, much improved alloys; this hardness corresponds approximately to a 6063 T8, which has a proportional limit of 265 MPa. Tests made on small specimens cut from the head lead to a value of 240 MPa. This maximum strength is between the ones of RR53 (sand cast) and RR50 (die cast - Table-2). However, it may depend on the heat treatment of the aluminum alloy of the cast: a modified RR50. For example, the 6063 alloy with a T8 treatment has twice the elastic limit of the T5 one. In fact, the 6063 alloy with a T5 treatment has approximately the same tensile strength of RR50 in Table 1. Therefore, with any probability, our head was made of modified (Si slightly enriched) RR50 with a similar treatment to the T8. The surface roughness of the head is consistent with sand cast. The richer silicon in the alloy of our head increases fluidity of the alloy during casting. In any case, it is a hypoeutectic alloy with low silicon. Probably the head was subjected to temper and subsequent aging (process in which Mg_2Si and $CuAl_2$ precipitates are formed). Many of the aluminum alloys harden spontaneously at normal temperatures after solution heat treating. Other, like the R.R.56, need a solution treatment was to quench from 530°C and ageing is carried out at 175°C. For R.R.50, the solution treatment could be omitted and the metal could be taken directly to precipitation hardening (155°C-170°C). However, given to the criticality of the component, it is probable that the full treatment cycle was performed on the head to obtain the best mechanical properties and to improve stability with temperature. In order to try to decipher the intentions of those who have selected such composition, one must reason on the properties of the individual elements. Pure aluminum has poor mechanical characteristics that make it unsuitable for industrial use. It is only used where corrosion resistance is required. Silicon is the main alligation element. It gives high fluidity to the alloy, which becomes the highest in percentages close to that of the eutectic (about 12%). The negative aspect is the decrease in tenacity due to the eutectic acicular shape. Today, with the technical progress, the silicon is made globular. In the WWII period the globular silicon was probably not available. It is possible, that, to improve fluidity, the RR engineer increased to the topmost the silicon quantity (for the available technology at the time). In addition, copper was taken near the maximum value possible. In fact, copper improves mechanical properties, but significantly reduces corrosion resistance. The iron improves the stability of the alloy; however, it tends to form intermetallic needle-shape formations. Nickel improves mechanical properties and melting temperature. It also increases the mechanical resistance to heat. The manganese exercises against the iron a buffer effect. Iron, as already pointed out, leads to the emergence of a very fragile needle structure. Manganese instead favors the formation of a branched structure with a considerable increase in toughness and ductility. Magnesium is important because it makes thermal treatment possible and improves corrosion resistance. From the micrographs of Figure-3, it is possible to see some of the aspects mentioned. A huge works seems to have been carried out to optimize the original RR50 aluminum alloy. The light gray background color represents the alpha primary aluminum phase, while the irregular zones are the eutectic aluminum silicon (Figure-3). Figure-3 also emphasizes the porosity of the cast, in many cases visible to the naked eye. In fact, one of the problems of aluminum is the sensitivity to gasification (it forms hydrogen) with porosity formations in the cast. Many of such porosities are visible in the micrograph of Figure-3 (black dots).

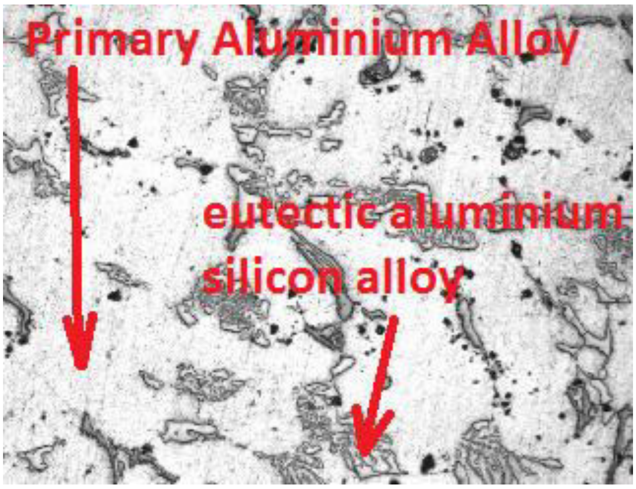

Figure-3. Optical micrograph of the head aluminum alloy x 200. Etchant $CuCl_2$. Porosities (black dots) are present in the head cast. Primary and eutectic aluminum Silicon.

MATERIAL PROPERTIES OF THE HEAD CAST

Normally, for materials suitable for the production of heads, tests are carried out to obtain a strength-temperature diagram and a Young-module-temperature one. In fact, the material undergoes remarkable variations of its characteristics with very marked decays. Also after cooling the material keeps trace of the thermal stress. In particular, the material softens when it is exposed to high temperatures above ageing. As the residual material hardness (strength) curve with temperature was not available, experimental tests were carried out to determine this curve. In any case, reference temperatures should be available. Luckily, the Mosquito FB had the problem of overheating at take-off. In operational mission an additional aircraft was warmed up to compensate for airplanes that had to “come back” early during the mission. This additional aircraft had to take off after the other ones. It was common that the additional aircraft could not take off due to overheating. In fact, as the coolant exceeds 140 DEG C, the pipes tend to leak and the engine has to be shut off. Temperatures of 135 degrees C were always reached at take-off and climb. In many cases, especially in long combat mission, the coolant temperature remained very high through the flight. In fact, from Mosquito FB VI Pilot's notes, on Merlin XX production engines the temperatures were: oil 90-105 degrees C; coolant 100 degrees C normal, 135 maximum during climb. These values are valid for Merlin 25, but they are reduced to 125 degrees C for Merlin 21 and 23. Therefore, the maximum temperatures on the surfaces of the head exposed to the coolant are known and can be used as reference to validate a reasonable "life" of the engine in hour. This value is successively used for the measurements that are made in the other areas. A reference set of specimens can be taken from a cool part of the head and can be seasoned in the oven at this reference temperature (135 degrees C). The time taken to reach the hardness of the "reference temperature surface" is the life of the engine. Therefore, this reference time is critical for all the other measurements. This reference time proved to be 35h for our head. This is the "estimated flying time" of our engine. It is consistent with the information send us by Serg. Robin Budworth RAF 23[th] squadron-historian on 2006, January 13[th]. The Authors wish to thank Mr. Budworth and Daniele Garavini for this information. Our Mosquito airplane was ferried first to North Africa, then to South Italy-Pomigliano-Naples and flow several missions of 2.5h each (approximately) before the fatal event.

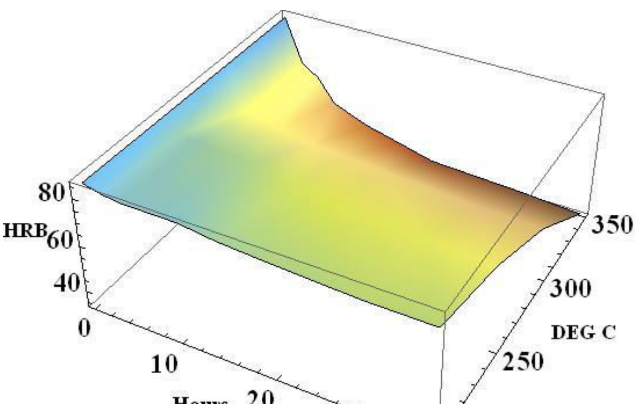

Figure-4. Reduction of HRB at Temperature (DEG C) for hours (Hours).

For the test, several small specimens were cut into non-thermally altered (cool) areas of the head. The first sets of specimens (Figure-5) were maintained at a constant maximum temperature of 350 DEG C.

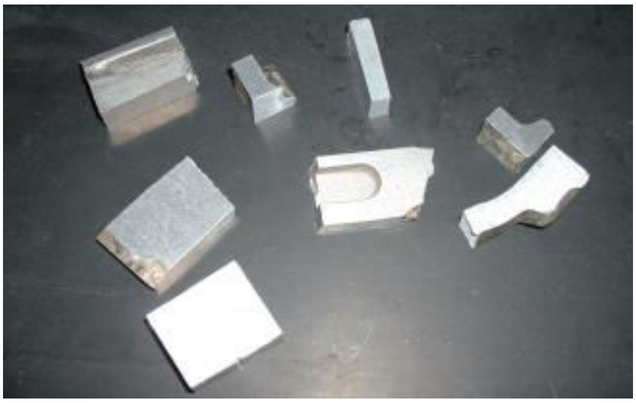

Figure-5. Extremely small test specimens for HRB-temperature graph of Figure-4.

At fixed time intervals (2, 4, 6, 10, 14, 18, 28, 35h), a few specimens were extracted from the oven, cooled in air, and HRB hardness was measured. In this way, the HRB temperature curve was obtained at the temperature of 350-degree C. The same tests were carried out for 300 DEG C, 250 DEG C, 200 DEG C and 135 DEG C. The results are summarized in Table-3 and Figure-4. For final validation, it was also checked that thermal cycling does not affect the residual hardness. In fact, it was found that the number of heating-cooling cycles does not significantly affect the residual hardness. The only relevant parameter is the maximum temperature-retaining-time. This fact is typical of many aluminum alloys. With the aluminum alloy residual stress vs temperature graph (Figure-4, Table-3), it is possible to evaluate the temperature field many relevant positions on the head. A detailed description of the combustion chamber surface is introduced in this paper.

VOL. 15, NO. 22, NOVEMBER 2020 ISSN 1819-6608
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Table-3. Residual hardness [HRB] vs. temperature [DEG C] and time [hours].

Time (h)	**HRB @ 200 C**	**HRB @ 250 C**
2	84	82
4	83	82
6	83	81
10	83	80
14	81	76
18	80	74
28	78	72
35	78	70
Time (h)	HRB @ 300 C °	HRB @ 350 C
2	68	67
4	66	62
6	65	52
10	62	46
14	61	42
18	60	38
28	57	36
35	56	34

HEAD TEMPERATURE AND HARDNESS

A RR Merlin cylinder head were then measured for HRB values as shown in Figure-6. Usually, the measurements are repeated on several heads, the maximum and minimum values are discarded and the others are arithmetically averaged. In this case, only one head (the most damaged one) was measured. Very low values of 37 and 47 HRB were found on the upper right exhaust values. These values are dubious and can be derived from small superficial defects on the cast. These small defects are quite common on old engines and they do not affect the engine functioning.

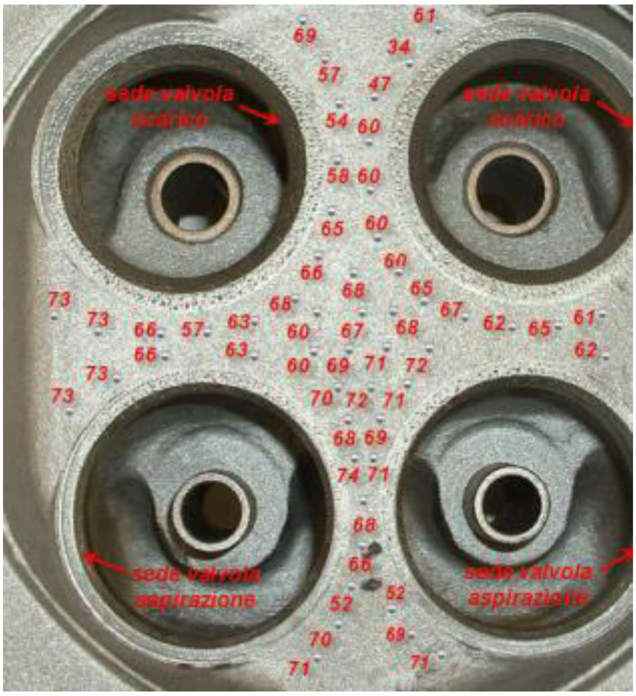


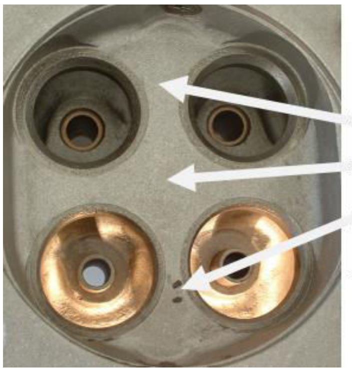
Figure-6. HRB measured at the different points. Intake valves below (smaller valve guides).

The corresponding temperatures are shown in Figure-7. The maximum temperature of 350 DEG G is to be discarded due to dubious hardness measure.

COMPARISON WITH NACA TN 2069

This method had been widely used in the past and today has been deemed as invalid. On the contrary, the Authors found that, for many aluminum alloys used in head cast, it is still valid and very useful for the design and development process. The RR Merlin XX test case was chosen due to the availability of NACA TN 2069"*Cylinder-head Temperatures and Coolant Heat Rejection of a Multicylinder Liquid-cooled Engine of 1650-cubic-inch Displacement"*. The engine of this NACA paper is the Merlin Packard V-1650-7 engine, which is a re-enginereed copy of the Mosquito engine (RR Merlin 70). NACA made temperature measurements with thermocouples at different points of the head. Data of refrigerant temperature measurements and mass flow through the heat exchanger are also available. NACA TN 2069 summarizes the experimental results in readable charts. These data are an authoritative term of comparison between our data and these "true values". The results are visible in Figure-7. As it can be seen, the temperatures from our method are slightly higher than NACA data. This result may be because the NACA engine was tested with a maximum coolant temperature of 115 DEG C. Our Mosquito did, probably, reach coolant temperatures up to 135 DEG C. In any case, NACA data are averaged by the measurement system (see Figure-8).

Figure-7. Temperatures (Degree C). Intake valves below (smaller valve guides).



This paper	NACA
320 C	288 C
280 C	252 C
250 C	242 C

Figure-8. Temperature comparison (Degree C).Intake valves below (smaller valve guides).

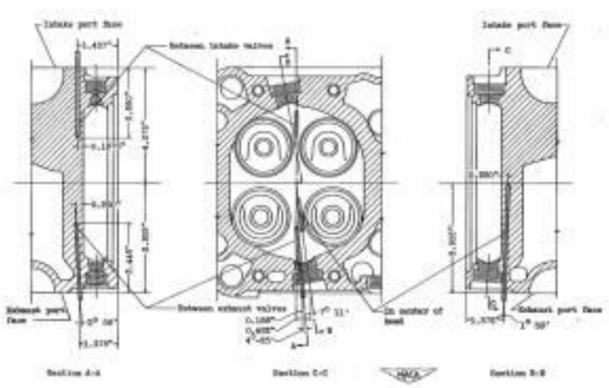


Figure-9. Figure 7 of NACA TN 2069 with thermocouple position.

Figure-9 shows that the thermocouples are quite "large". For structural reason the measure points are inside the head. Even with the best calibration, these measured temperatures tend to be lower than combustion chamber surface ones. Furthermore, the NACA paper is quite old (1950) and the instrumentation of that period was rather inaccurate for modern standards. For all these reasons, the values obtained with our method should be regarded as reasonable. In addition, service temperatures are often higher than brake ones due to many factors: cooling installation efficiency, inertia effect and transient loads. In the case of the Mosquito, for example, it was well known that it tended to overheat on ground, with the spare airplane that has to be shut off earlier due to overheating in many missions. In addition, this particular airplane faced two single-engine emergency flights, being the second the fatal one. The Mosquito is a fighter-bomber with remarkable performances at high-speed. For operational reasons, flying over the enemy territory, often at low altitude, the engines were stressed for long time. The Meredith cooling system, with radiators embedded in front part of the wing between the fuselage and the engines, was particularly efficient in transforming waste energy in additional thrust. Unfortunately, as in modern Formula 1 cars, the system works best with high coolant temperatures. In fact, the Meredith duct is a static jet engine with the combustion chamber replaced by the radiators. As in jet engines, thermodynamic efficiency depends on maximum temperature of the cycle. For this reason, a continuous challenge takes place between the aerodynamic technicians and the engine people. From Author experience the result is always on the side of the aerodynamic people and of high performance. The Mosquito is a typical example of this policy, being safe from its extraordinary velocity. Unfortunately, this fact came at a price: engine coolant temperature. Luckily, the RR Merlin was a particularly reliable engine with only one weak point: durability. In fact, after WWII the Merlin engine had short life in general aviation. Operational temperatures on vehicles are always higher than brake-ones; it happens on most vehicle installations. Therefore, the results obtained in this paper may be even more accurate than the NACA ones, at least for the Mosquitos. The process required a very small amount of work-hours. The very accurate results obtained even on a single, very old, heritage engine with very little head-material are the best confirmation of the validity of the residual hardness method [3-19].

CONCLUSIONS

Material properties depend on temperature, stress and stress time derivative. This paper analyses the head of a Mosquito engine head. The experimental head temperatures are compared with the ones of a NACA document on a Rolls-Royce-Merlin-70 Packard-built engine. This experimental method is based on residual hardness measurement on a head of a RR Merlin that crashed in San Marino during WWII. A few samples from a "cool" part of the head give the initial "thermally intact" hardness. For this purpose, a set of "cool part" samples were kept in at the maximum constant temperature of the coolant (135 degrees C). A few specimens are extracted from the oven at regular time intervals and the residual hardness is evaluated. The time interval matching the hardness of the original cooled surfaces gives the engine working life. In this way, a reference term of hour logged by the engine is obtained. Other "cool part specimens" are kept at several values of temperature for the working life of the engine. The residual hardness is measured for these specimens. Therefore, a correlation between residual hardness and temperature is obtained for the specific engine alloy. It is then possible to measure the residual hardness of various points of the head and to obtain the maximum temperature reached. In general, experimental tests have confirmed the cost-effectiveness of this approach. The NACA TN 2069 data and those measured with this method show an extremely good correlation.

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