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Materials Selection by Competitive Analysis of Properties: A Laboratory PBL Experience in Materials Science and Engineering*

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The case study shown here was proposed by the author as the final teamwork activity for a Materials Science and Engineering course in the third semester of an Industrial Engineering degree. It was presented as an experimental problem on materials selection that the students had to solve by fabricating a piece with fixed dimensions and fulfilling three limiting properties. Specifically, these were thermal, electrical and mechanical requirements, chosen to rule out in principle most polymers, metals and ceramics, respectively. The experiment intended to emphasize that materials selection often involves a competition between properties, that leads to mutually excluding solutions. It was carefully designed as an ill-structured problem with no unique correct solution. Nevertheless, a composite made by appropriately combining two or more materials from the three classical families can fulfill the required conditions. The paper shows and discusses the particular solutions proposed by my undergraduate students. Along the search they found out a number of essential topics in Materials Engineering, such as the difference between surface and bulk properties, the ranges of service temperature of common materials, the problem of ceramic-metal bonding, or the main factors affecting thermal shock resistance. They had to purchase the ingredients and fabricate the final samples by themselves, so inexpensive materials and rudimentary processing techniques were used.

Keywords: materials selection; problem-based learning; materials science and engineering

1. Introduction

Every day engineers face the problem of selecting the appropriate materials for a specific application, component or device. It is a complex task that involves evaluating the interrelationship between their properties, shape, processing technique and cost. Even taking into account only the material intrinsic properties, the selection forces to prioritize a particular requisite and set the other requirements aside.

Quite often a preliminary approach allows focusing on just one of the three classical families of materials, as they present a clear advantage over the others –and one "Achilles' heel". Namely, ceramics are hard although brittle, metals are tough but sensitive to corrosion and creep, and polymers are cheap and flexible but have low operation temperatures. After this basic choice, a combination of different properties can be required. In this case a common strategy is the use of Ashby's charts, in which the selection is assisted by mathematical operations involving several parameters and its graphical representation [1].

The case study presented here is a relatively simple materials selection experimental problem that, however, clearly reveals that the fulfillment of several requirements involves a competition. It was intended for third-semester Industrial Engineering students and formulated at the beginning of the course, when their background in Materials Science was limited to elementary or intuitive concepts supported by a basic training in Chemistry and Physics. However, the students had to present their results at the end of the semester, so they attended the theoretical lectures trying to find hints to solve the challenge. In this sense it can be considered a problem-based learning (PBL) laboratory exercise.

PBL is an instructional method in which a particular problem statement is the starting point of the learning process, which takes place through its guided solving by the students. Although there is a wide range of PBL models [2], the main elements common to this approach are [3]: (1) a relatively complex problem with many possible answers is presented, (2) the students work in collaborative groups to search for the solution, and (3) the students direct their own learning process in an active way while the teacher plays the role of a facilitator.

PBL has been often used in Engineering education for the last fifty years, as shown in the thorough review recently published by Chen et al. [4]. However, examples of PBL in Materials Science and Engineering (MSE) at the undergraduate level are relatively scarce. In the seminal works by Henry et al. [5, 6] and in few other examples [7, 8] PBL has been used as the instructional approach for a whole

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MSE course but with negligible experimental content. Only a few of the published PBL experiences deal mainly with laboratory activities [9, 10]. The case presented in this paper is basically experimental and limited to a small part of the competences required to the students.

2. Presentation

2.1 Statement of the Problem

The students had to form teams with three or four members each. They were given the mission of making one piece per group fulfilling particular requisites. The final specimens should be prepared along an 8-week period. Although they were encouraged to fabricate the pieces by themselves, any commercially available material was accepted.

The problem was stated through a dimensional condition and a succession of three tests:

Geometrical constraint: The required sample must be a prismatic bar with approximately square basis not larger than 5×5 mm^2, and between 55 and 70 mm long.

First condition: The specimens must undergo a 3-minute treatment in a pre-heated furnace at 300°C, followed by a quick quenching into water at room temperature.

Second condition: After a gentle drying process with a soft cloth, the pieces at the end of the previous test must be electrically insulating. The specific condition was that the DC electrical resistance measured with a commercial ohmmeter between any two surface spots at 1 cm distance be larger than 1 kΩ.

Third condition: The surviving specimens must show the highest possible fracture toughness as measured in a Charpy impact test with 300 J initial energy.

2.2 Assessment

The main deliverable of this challenge was a physical specimen. Numerical grades were assigned after the tests, according to these criteria:

1. If a bar size didn't fit the dimensional limits, its final mark was 0.
2. The samples destroyed in the thermal treatment or being electrically conducting would get 3/10.
3. The final grades for the rest of the specimens were relative to the others and depended on the numerical result of the impact test, being 5/10 for the sample with minimum absorbed energy and 10/10 for the one reaching the maximum value.

Given the experimental approach of the problem, the students were given the opportunity to test their prototypes in the lab several times before the final presentation. They were also required to present a written report with the explanations and justifications of the material and fabrication details.

Fig. 1 summarizes the conditions and the assessment criteria.

2.3 Preliminary Analysis of the Limitations

As it can be seen from the previous sections, the ultimate goal is to obtain a sample with fixed dimensions and the maximum possible impact toughness (third condition). Most probably the students of an introductory MSE course have an unclear idea of toughness – the ability of a material to absorb energy and plastically deform before fracturing. However, they know that, as a rule,

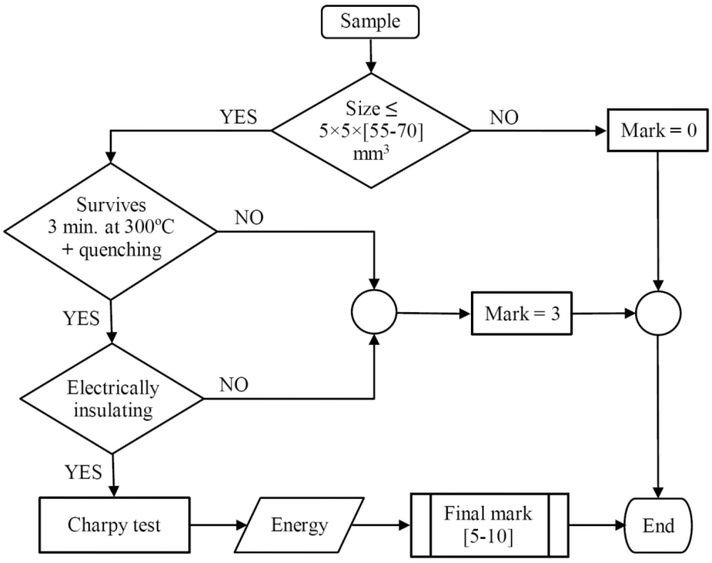

Fig. 1. Flow chart showing the conditions and the assessment criteria explained in sections 2.1 and 2.2.

Table 1. Preliminary analysis of the limitations imposed by the three conditions

Condition	Goal	Materials ruled out	Potential candidates
First	Melting or decomposition temperature higher than 300°C	Most polymers	Ceramics and metals
	Large thermal shock resistance	Some ceramics and glasses (depending on dimensions)	Mainly metals and alloys, and some polymers
Second	Electrically insulating	Metals, alloys and some semiconductors	Ceramics and polymers
Third	Maximum impact toughness with fixed dimensions	Ceramics (brittle) and polymers (low strength)	Metals and alloys

ceramics are brittle and polymers have low tensile strength and thus both families show low resilience – a magnitude that combines both ductility and strength and is closely related to toughness [11]. Thus, the search for a tough material guides them intuitively into the family of metals. As a matter of fact, the Charpy test is mainly used with metals and alloys [12], has limited application with polymers [13] and is almost never applied on ceramics. It is worth mentioning that, for the sake of simplicity, the impact test proposed here is not a true Charpy test, which requires machining each specimen with a well-defined V-shaped notch. This would complicate the fabrication process for the students and the comparison between samples. Nevertheless, we used a standardized Charpy apparatus allowing the measurement of the amount of energy absorbed by the sample during the fracture process under triaxial load conditions at high strain rate. Also the common 10×10 mm^2 section of the Charpy specimens was modified here to avoid excessively high values of the absorbed energy –at the expense of complicating the fabrication process.

For the dimensions required, the second condition excludes materials with electrical conductivity $\sigma > 0.4\ \Omega^{-1}\mathrm{m}^{-1}$ at room temperature. Pure metals and alloys present conductivity values in the range 10^6–$10^8\ \Omega^{-1}\mathrm{m}^{-1}$ [11] and thus must be rejected (even considering a huge probe-sample contact resistance during the measurement). The remaining possible candidates are insulators and some semiconductors, which belong to the groups of ceramics or polymers. Special care had to be taken with water-absorbing specimens, which could show high apparent conductivity values as a result of insufficient drying.

In consequence, the mechanical and electrical requisites (second and third condition) seem to be mutually excluding, revealing the first competition in this materials selection problem.

Furthermore, in order to fulfill the first condition the material chosen must have melting or decomposition temperature higher than 300°C, or at least resist this temperature for the relatively short 3-minute period. Most polymers must be discarded. Even more, the additional requisite of large thermal shock resistance under abrupt cooling is not trivially fulfilled by all ceramics and glasses with these dimensions.

In conclusion, the three conditions come together to rule out any simple choice of a single-phase material: most polymers and metals will fail the thermal treatment or the electrical test (and thus get 3/10 mark), and ceramics will reach the impact test but will absorb a very low energy (giving around 5/10 mark). Table 1 summarizes this preliminary analysis of the limitations imposed by the three conditions.

As I will show in the following, a reasonable approach to solve this problem while obtaining high grades is preparing a composite through the combination of materials from the three classical families. Before going on, I suggest the readers to imagine first their own materials selection.

3. Results

The students were organized in fifteen teams, numbered 1 to 15. They had received a general training in laboratory safety at the beginning of the semester. In every lab activity they wore personal protective equipment and were under constant supervision by the instructors.

Fig. 2 shows a photograph of the corresponding as-received samples. All of them fulfilled the geometrical conditions and went into the second round.

The following is a short description of the solutions proposed by the students. In Section 4 I will discuss them in detail.

Group 1: composite sample prepared with a steel core (cylindrical bar 2.5 mm in diameter taken from a screwdriver) coated by Ceys® refractory putty.

Group 2: anodized aluminum bar (the anodization process was carried out by the students).

Group 3: composite prepared with a Cr-V steel bar (taken from a hex key) and a clay coating.

Group 4: EN C22 (AISI 1020) low-carbon steel coated with a silicone-based high-temperature resistant spray paint (trademark FM).

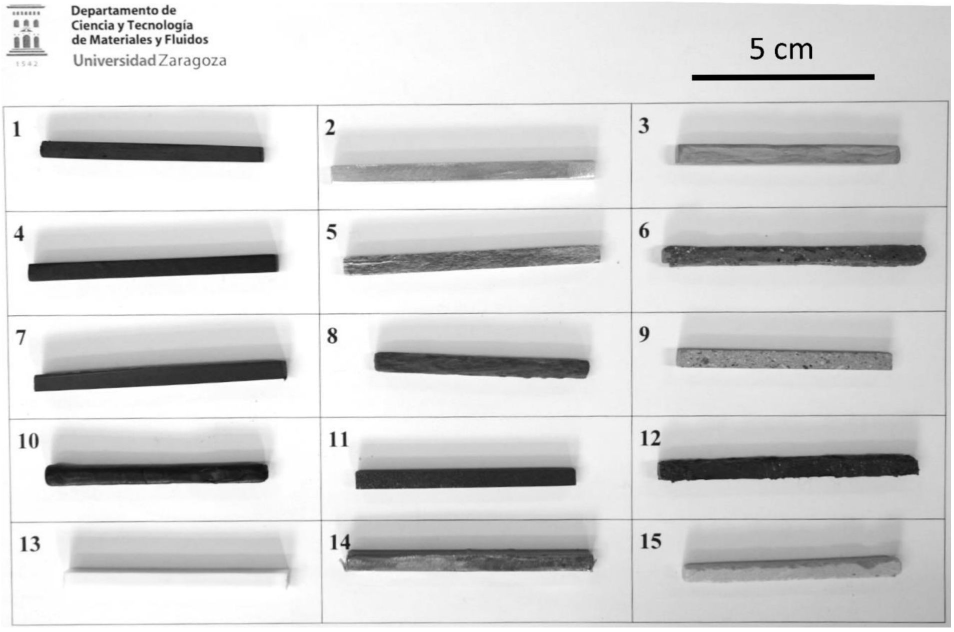

Fig. 2 As-received specimens of the fifteen groups.

Group 5: bar of a commercial composite made of glass-fiber reinforced epoxy matrix.

Group 6: circular-section steel bar of unknown composition coated with refractory cement.

Group 7: commercially available composite containing 80% polytetrafluoroethylene (PTFE), 15% glass fiber and 5% MoS_2.

Group 8: EN X5CrNiCuNb16-4 (AISI 630) precipitation-hardened martensitic stainless steel rod coated with high-temperature resistant sealing putty.

Group 9: bar of refractory brick.

Group 10: EN 42CrMo4 (AISI 4140) steel core with 4.0×4.0 mm^2 section, coated with commercial ''polymeric clay'' of unknown composition.

Group 11: square-section bar taken from a car brake pad (unknown composition, trademark Ferodo).

Group 12: EN 42CrMo4 steel core with 4.5 mm × 4.5 mm section, with silicone-based high-temperature resistant coating from Würth®.

Group 13: PTFE bar drilled longitudinally and then filled in with a round-section rod of EN C22 steel.

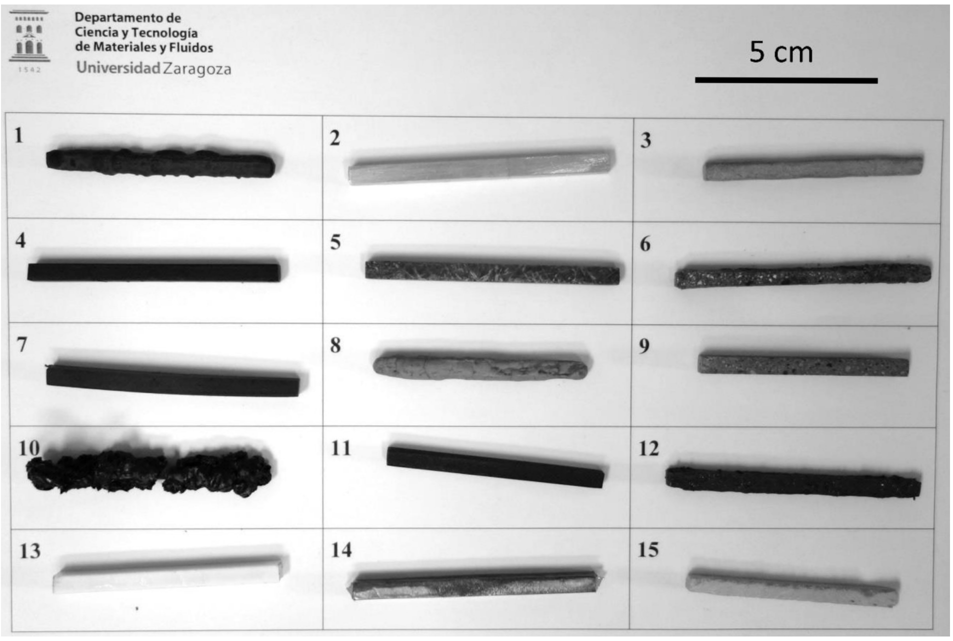

Fig. 3. The samples after the thermal treatment.

Table 2. Values of energy absorbed in the impact test

Sample number	Energy absorbed (mJ)
1	10
2	16
3	36
4	40
5	1
6	21
7	2
8	20
9	0
10	21
11	0
12	43
13	12
14	49
15	0

Group 14: EN X5CrNiMo17-12-2 (AISI 316) austenitic stainless steel covered with a thin adhesive film of Kapton®.

Group 15: square-basis bar of a porcelain tile.

Their appearance after undergoing the thermal treatment can be seen in Fig. 3. The values of the energy measured in the impact test are listed in Table 2, and the specimens at the end of the overall process are shown in Fig. 4.

4. Discussion

A detailed analysis of the results presented by the fifteen groups is presented in this section. They are arranged in families and summarized in Table 3.

4.1 Monolithic Specimens

The simplest family of results contains the "monolithic" specimens, i.e., those made of one single material. No student decided to present purely polymeric or metallic samples. They supposed that these materials would fail the high-temperature test in the first case or the insulation test in the second, which would give them a relatively low (3/10) mark. However, two groups (9 and 15) prepared monolithic ceramic samples which fulfilled the first and the second condition and could then stay in the competition. They prepared the samples cutting and sanding a refractory brick tile and a piece of porcelain, respectively, until the desired dimensions –a rather tiring but simple processing technique. These students chose a low-risk solution assuring 5/10 but with little hope of getting higher marks. In fact, as they probably expected, the energy absorbed in the impact test was zero in both cases –within the experimental accuracy.

4.2 The Most Common Solution

The largest set of samples contains those consisting

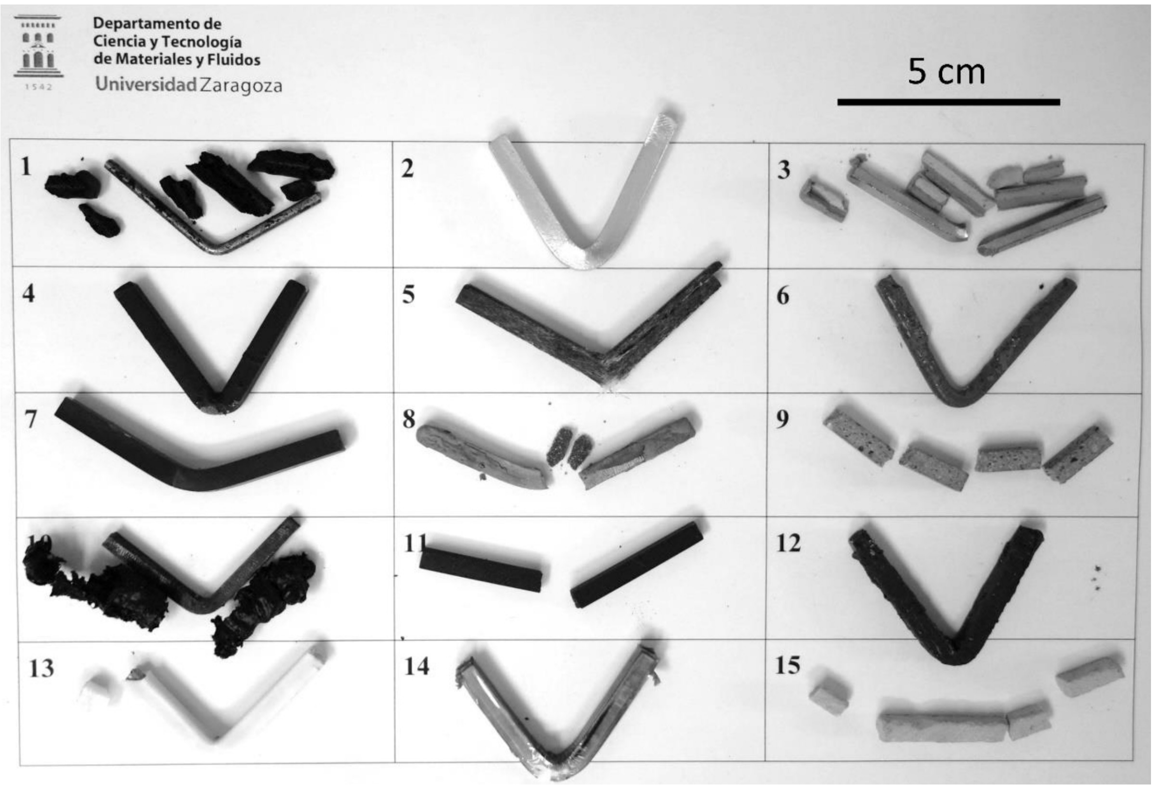

Fig. 4. The samples at the end of the whole process.

Table 3. Summary of the solutions presented by the fifteen groups

Type of solution	Specific composition	Groups	Advantages	Drawbacks
Monolithic ceramic sample	Grinded bar of a refractory brick or porcelain tile	9, 15	Stands thermal treatment and quenching. Electrically insulating. Mark $\geq$ 5/10 is ensured	Very hard: long grinding process needed. Very brittle: energy absorbed around 0 J
Steel core	Plain low-carbon steel	4	High ductility. Low price	Moderate impact toughness
	Precipitation-hardened martensitic stainless steel	8	High hardness and tensile strength	Moderate ductility and impact toughness
	EN 42CrMo4 quenching and tempering steel	10, 12	Relatively high impact toughness	Thermal history unknown. More expensive than plain carbon steel
	AISI 316 austenitic stainless steel	14	Record value of energy absorbed. Combined with a clever choice of coating	Relatively expensive
	Steel of unknown composition	1, 3, 6	Pieces obtained from common objects	Moderate ductility and impact toughness
Polymeric coating on steel	Polymeric paint	4, 12	The good adherence and high ductility of the coating avoid detachment during quenching. Can be applied as a thin layer	Unknown composition: potential risk of degradation at high temperature
	"Polymeric clay"	10	Can be molded easily	Did not resist thermal treatment
	Kapton-HN®	14	Very high service temperature and large ductility. Passed 300°C treatment. No detachment during thermal shock. Small thickness (50 μm)	None
Ceramic coating on steel	Clay, cement, high temperature-resistant sealing putty	1, 3, 6, 8	Can be molded around the core. Resist 300°C	Poor ceramic-to-metal bonding: risk of detachment during quenching. Cracks.
Drilled PTFE	Longitudinally drilled PTFE block filled with low-carbon steel bar	13	Resists 300°C. No detachment during quenching. Electrical insulator	Relatively small diameter of steel core (3 mm)
Anodized aluminum	Anodized aluminum alloy (anodization carried out by the students)	2	Excellent electrical insulator. No additional coating required. Perfect bonding.	Relatively low toughness of aluminum
Commercially available composites	Glass fiber-reinforced epoxy-matrix composite	5, 7	Electrically insulating. Passed 300°C treatment	Very low impact toughness
	Bar machined from a brake pad (unknown composition)	11	Passed the thermal and electrical tests	Very high hardness and very low toughness

of a steel core surrounded by an insulating, high-temperature resistant coating (1, 3, 4, 6, 8, 10, 12 and 14). Perhaps this is the most intuitive solution. Given that the electrical test is a *surface* measurement but the mechanical one explores a *bulk* property, a specimen made of a tough core coated with an insulating layer will fulfill the electrical condition and succeed in the Charpy impact test. In order to verify also the first condition, the coating material must be able to resist the 300°C test followed by quenching in water, without detaching.

The mechanical behavior of this home-made composite is determined mostly by the properties of the core. The absorbed energy can be maximized by playing with both its composition and dimensions. Steel is a straightforward choice as a tough material and this seemed to be clear for most students. In fact, the samples with the highest values of energy absorbed in the Charpy test belong to this family, with 30 J in average (see Table 2).

As for the dimensions, the maximum side of the square section is 5 mm, but this length includes the core and the coating. For the same composition of the central part, and neglecting the influence of the coating on the mechanical properties, the absorbed energy will increase with increasing its section area. Thus, maximizing the transverse section of the core is a good way to achieve an optimal solution. This implies making the coating as thin as possible, although it is clear that its nature poses a lower limit to this thickness (as will be discussed later). An interesting example of this geometrical competition is the comparison of the solutions presented by groups 10 and 12, using nominally the same steel. The sample with around 20 mm^2 core section absorbed twice as much energy as the one with 16 mm^2. It is worth mentioning that EN 42CrMo4 is a quenching and tempering steel, but the authors did not provide details about possible thermal treatments, that could have originated differences between the intrinsic properties of the material in both samples.

Let's discuss in more detail about the choice of a particular alloy. Groups 1, 3 and 6 gave scarce or no information about their samples composition. In the first two cases the origin of the pieces (a screwdriver and a hex key, respectively) allows to suspect that they belong to the family of tool steels. Their sections are very different both in shape and dimensions (as is clearly visible in Fig. 4), which could be the origin of the large difference between the values of absorbed energy (10 J *vs.* 36 J). Sample Nr. 6 was made of steel of unknown composition and absorbed 21 J.

The core of sample Nr. 4 (energy absorbed: 40 J) was made of C22. This plain carbon steel contains 0.2% C and shows a good combination of strength and ductility (around 450 MPa of ultimate tensile strength and 17% elongation at break, in normalized state). It is thus a reasonable choice from the point of view of the mechanical behavior. Moreover, this would be by far the less expensive option among the selected steels – although the economic considerations were not included in the statement of the problem.

Nr. 8 (energy absorbed: 20 J) was made of X5CrNiCuNb16-4, a precipitation-hardened martensitic stainless steel – often denoted 17-4 after its Cr-Ni percent content. It has high hardness and tensile strength but moderate values of plastic deformation. In spite of the thick core of this sample (about 4×4 mm^2), its relatively low ductility was probably the reason for the modest result obtained in the Charpy test.

Samples Nr. 10 and Nr. 12 absorbed 21 J and 43 J, respectively. They were made of 42CrMo4, a low-alloy steel containing 0.4% C and small amounts of Cr, Mo and Mn for improved hardenability. It exceeds 1 GPa tensile strength and 18% elongation at break after normalization [11], although these values are often modulated through quenching and tempering. So this steel is also a very good choice, although more expensive than the plain carbon steel mentioned before. The likely influence of the geometry of both samples on their Charpy results was discussed above.

The record value of energy absorbed in this experience (49 J) was obtained in sample Nr. 14. Its central part was made of AISI 316, a widely used austenitic stainless steel showing the highest values of resilience among common metals as a consequence of its very high ductility (appropriate thermal treatments allow to get 40% elongation at break, while keeping 500 MPa of tensile strength). The main problem faced by the authors of this sample was the mechanization of the steel piece. However, they wisely optimized the alloy selection and the thickness of the core piece (which, in turn, was possible through a clever choice of the coating material).

Comparing real numerical data of materials properties is, in my experience, very instructive for Engineering students. For instance, they realize immediately the common compromise between strength and ductility just by inspection of a table with mechanical data. Many databases with plenty of information of common engineering materials can be found in modern introductory MSE textbooks [11, 14]. However, the students often prefer the internet, so I suggest them a number of reliable websites such as the online-accessible table [15] accompanying the textbook by Smith and Hashemi [14]. In that database it can be found that AISI 1020 and AISI 316 show the highest values of energy absorbed in the Izod impact test – somehow similar to Charpy test – among the alloys discussed here.

4.3 Coating Materials

Regarding the coating composition, its insulating or semiconducting nature leads the selection process towards polymers or ceramics. Probably the students knew that few polymers can be used above 300°C without melting or decomposing, but several groups found commercially available exceptions. This is the case of the high-temperature resistant paints chosen by groups 4 and 12. They presented them as "silicone-based" but provided few compositional details apart from their tradename. Group 4 chose an anticaloric spray paint (from FM^{TM}) often used for the protection of metallic parts exposed to heat, such as exhaust pipes, stoves, etc. Group 12 used red "Silicone special 250" from Würth^{TM}, with application as a sealing compound in the automotive industry. Both coatings passed successfully the 300°C test, indicating that their degradation or melting temperature is larger than this value. In spite of the large thermal expansion coefficient mismatch between polymers and metals, the high ductility of both coatings avoided their detachment after quenching in water. Remarkably, these paints can be applied in the form of very thin layers, allowing the steel core to be very thick (about 4.5 mm side). Combined with a good choice of the steel, as explained before, samples 4 and 12 got excellent results in the impact test (more than 40 J). The adherence between the core and the film was very good even after the Charpy test, as can be seen in Fig. 4.

The material used by group 10 for the coating was a black putty advertised as "polymeric clay", but no details were provided about its composition or trademark. This putty can be molded easily and becomes rigid after thermal treatment, thus resembling the hydroplasticity and sintering of ceramic clay. However, the catastrophic result of the 300°C test on this piece – as can be seen already in Fig. 3 – suggests that the coating was not made of true, inorganic clay. Miraculously, the surface remained insulating in spite of its foam-like appearance after quenching in water.

Group 14 used a coating made of Kapton®, a widely used flexible polyimide film developed by DuPont™ that remains stable in a broad temperature range [16]. Among the several types commercially available these students chose a 50 μm-thick adhesive tape of Kapton-HN, that can be used up to 400°C. This sample passed the furnace test and subsequent quenching without apparent degradation or thermal shock-induced detachment, as a result of the unusually high service temperature combined with large ductility. Moreover, the small thickness of the film enabled the students to use a steel core with 4.9×4.9 mm^2 section. This sample got the highest mark (49 J in Charpy test).

Four groups chose ceramic materials to coat the steel core. The samples were made by wrapping the core with plastic mass and using different homemade molds to reach the desired shape. From the very beginning the main trouble found by these students was the poor ceramic-to-metal bonding. This well-known problem appeared already in the conformation at room temperature, increased during the drying process, and became critical in the quenching tests, where differential thermal expansion increases the risk of detachment. Sample Nr. 3 was prepared with mineral clay applied carefully on the steel piece and heated very slowly to remove water and begin the sintering. Group Nr. 6 chose high-temperature resistant cement (Bricocem™, commonly used to fix refractory bricks) and prepared their specimen in a similar way. In both cases small cracks were clearly visible after quenching, but they were not enough in number or size to make the samples conducting according to the second condition. Groups 1 and 8 used commercially available refractory sealing putties. According to the manufacturers, both are stable up to at least 1000°C and present excellent adhesion on metal surfaces. However, in the first case the thermal-shock treatment damaged considerably the coating (Fig. 3), although it remained attached and insulating. The brittle nature and weak adhesion of all these ceramic coatings was apparent after the impact (Fig. 4).

4.4 A Couple of Creative Solutions

It is well known that one of the most common problems arising with coatings is adherence with the substrate. In fact, some of the samples discussed above suffered the limitations of poor metal-ceramic or metal-polymer bonding. In order to avoid these drawbacks while keeping the idea of a metallic core and an insulating surface, two groups explored more original solutions.

Group 13 used a really unique approach. First they searched for a polymer resisting the electrical and the high-temperature test and found in the textbooks that pure PTFE melts at 327°C [11]. In addition, it is a good electrical insulator and can be machined with relative ease. So they prepared a solid PTFE bar with 5×5 mm^2 square section and verified experimentally that it fulfilled the thermal requirement. A C22 low-carbon steel bar 3-mm in diameter was chosen to become the core of the composite sample. Using a machining tool they managed to drill a longitudinal "tunnel" along the plastic piece without lateral pinholes, and filled it with the metallic rod of equal section. The steel selected is quite ductile but has moderate strength, and the energy absorbed in the impact test (12 J) was modest. However, the complexity and originality of the fabrication process (which required many unsuccessful trials) is remarkable. It is worth mentioning that other groups suggested similar solutions using wood instead of PTFE, although they didn't put them into practice. Wood is certainly a good insulator, has ignition temperatures in the range 350–450°C [17] and can be machined easily, so it would be a reasonable choice. Most likely, the problems arising from the electrical behavior of wet wood dissuaded the students from using it.

Another innovative solution was found by group 2. The students asked me how to carry out the anodization process of aluminum, one of the lab sessions in the fifth-semester Materials Technology subject of the Industrial Engineering degree in the author's University. They got an aluminum bar (the exact alloy was not specified) with 5×5 mm^2 square section and I showed them how to use the experimental setup to anodize it. After half an hour in diluted sulfuric acid under a voltage of 5 V, the surface electrical resistance between any pair of points was beyond the measuring limit of a commercial ohmmeter. The sample remained insulating after several attempts to scratch the coating, showing the excellent adhesion between the metal and the oxide layer. The value of 16 J for the energy absorbed in the Charpy test was moderate, but in my opinion this was the most imaginative solution among the fifteen groups.

4.5 Commercially Available Composites

Three teams made their sample using commercially available composites. Specimen Nr. 5 was machined from a block of glass fiber-reinforced epoxy-matrix composite. It passed the furnace test, showing that either the degradation temperature of the epoxy was above 300°C (as is relatively common in thermoset epoxy resins) or it could resist this temperature for a short period of 3 minutes. After drying, it was also electrically insulating. However, it only absorbed 1 J in the Charpy test. Despite its low impact toughness, this sample was extremely light, so its *specific* toughness would probably be more competitive. Indeed, composite materials often have excellent mechanical properties per unit weight. Unfortunately for this group, the problem statement posed a limitation on the maximum size of the sample, not on its maximum weight.

Also sample 7 was made of a glass-fiber reinforced composite, although in this case the matrix was PTFE. As explained before, this polymer melts above 300°C and is a good electrical insulator, so the sample fulfilled the first and second condition. This composite contained an additional 5% MoS_2, a filler commonly used to improve the tribological behavior of PTFE-based composites [18]. In spite of the complex structure and composition of this sample it presented very low toughness (2 J absorbed in the impact test).

Group 11 probably mixed up the concepts of resilience and hardness (or maybe wear resistance), which explains their choice for a complicated material taken from a brake pad. The authors did not provide details on the sample composition – nor the time devoted to machining it! Modern brake pads are made of a variety of composite materials for controlled friction coefficient, efficient heat dissipation and high wear resistance [19]. They often consist of a resin matrix reinforced with either polymeric or metallic fibers. So this strange sample did not even ensure the success in the thermal and electrical test, although fortunately it passed both of them.

5. Summary

The laboratory PBL experiment proposed here was intended to stimulate the creativity of students in an introductory MSE course at the initial stages of an Engineering degree, when their background in Materials Science is quite limited. They were asked to fabricate by themselves a specimen with thermal, electrical and mechanical properties carefully chosen to rule out most single-phase materials. This problem does not have a unique solution. For instance, many home-made composites fabricated with a combination of a metal core and a polymeric or ceramic surface can fulfill the required conditions and lead to satisfactory marks.

The main formative goal was to emphasize that competition is inherent to any material selection problem. However, the students became aware also of a number of essential topics in Materials Engineering, such as the difference between surface and bulk properties, the ranges of service temperature of common materials, the ceramic-metal bonding problem, the main factors affecting thermal shock resistance, or some rudimentary processing techniques.

6. Conclusions

Engineers have to solve problems. Indeed, problem-based learning is commonly used in Engineering education. In the field of Materials Science, PBL has been often used as the instructional procedure for a whole course but with very limited experimental content. The case study presented in this paper suggests a relatively novel approach focused on experimental activities which involve the manual preparation of samples and the characterization of their properties in the laboratory. A complex statement with carefully designed requirements was presented at the beginning of the semester. The students had to work in groups and the final marks depended on the degree of fulfilment of the required properties. Each group was allowed to participate with only one specimen, so they selected the most successful result after a long search process in which they experimented with many alternative solutions. In my opinion, every failure in this trial-and-error process was as fruitful from the educational point of view as the final solution itself. Moreover, all the students learned from the presentations and explanations of the other groups.

The experience was intended as complementary to lectures and other course activities, not as the educational strategy for the whole semester. Anyway, I believe that MSE instructors can take this case as a starting point to design similar problems adapted to their particular teaching strategy.

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