Materials Research. 2022; 25:e20220275
DOI: https://doi.org/10.1590/1980-5373-MR-2022-0275

Evaluation of 6000 Al Alloys for Application in Chassis of Electric Vehicles

Felipe Escher Saldanha[a], Sarah de Albuquerque Sousa[b], Guilherme Lisboa de Gouveia[b], Mauricio Dwek[c], José Eduardo Spinelli[a,b]*

[a]Universidade Federal de São Carlos (UFSCar), Departamento de Engenharia de Materiais, 13565-905, São Carlos, SP, Brasil.
[b]Universidade Federal de São Carlos (UFSCar), Programa de Pós-Graduação em Ciência e Engenharia de Materiais, 13565-905, São Carlos, SP, Brasil.
[c]Ansys, 69100, Villeurbanne, France.

Received: June 12, 2022; Revised: August 22, 2022; Accepted: October 18, 2022

The market for electric vehicles is growing, seen as the best alternative to replace internal combustion-powered vehicles. Recent developments in electric vehicles have allowed them to reach a level of performance, comfort, and safety that enables them to compete with traditional vehicles. However, several studies are directed towards increasing the autonomy of these vehicles, aiming at weight reduction of structural components. Aluminum alloys are increasingly being chosen to produce structural elements, due to their low density and suitable properties. The 6000 Al alloys are often used in chassis and bodywork. In view of this, this work proposes a comparison of 6000 series alloys, by means of thermodynamic (using Thermo-Calc®) and property computations (Ansys® Granta EduPack and Selector) to select the best alloys considering application properties, processability, and environmental impact. It was observed that the T6 heat-treated alloys presented better mechanical properties, but, on the other hand, they have more impact on the environment. As such, the 6010-T6 alloy was classified as the best alloy regarding performance, the 6061-T4 alloy the best in terms of processability, and the 6009-T4 alloy presented the lowest environmental impact. The 6111-T4 alloy was highlighted as the alloy showing the best balance between the examined properties.

Keywords: *Electric Vehicle, 6000 Alloys, Industry 4.0, Environmental Impact.*

1. Introduction

Currently, new products are being shaped around new social concepts, which involve new user profiles, greater safety requirements, and environmental awareness, among others. An example of this can be seen in the automotive industry, where the demand for electric vehicles has grown in recent years due to the need to replace fossil fuels, in view of environmental factors[1-3].

To keep the electric vehicle trend going, the industry still has to cope with autonomy limitations, battery recharge times, and limited power. The potential of this technology is enormous, but it still needs adjustments to overcome the use of internal combustion engines[3]. Some of those limitations can be addressed by industry 4.0 based on its key technologies, which include artificial intelligence, cloud computing, the internet of things, advanced robotics, systems integration, and computing integrated systems.

Different computation software can be used together in a complementary fashion, bringing different information and interpretations to the same situation. An example of this can be coupling thermodynamic computation results generated by the Thermo-Calc® software (analyzing the phases and possible compositions and microstructures of the alloys) with plots conducted by the Ansys® Granta EduPack and Selector software. As a consequence, it is possible to create robust comparison charts of properties of interest, prices, energy costs, and other environmental factors[4,5]. Thermo-Calc® works based on a set of databases. It is centred on thermodynamic equilibrium calculations, being able to build phase diagrams, among other phase and path analyses. It is very useful in order to improve/comprehend solidification and solid-state behaviors of various materials[4]. The Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022 is widely employed for improving materials and process engineering learning. The software has a vast and robust database that provides great assistance to teachers, students, and professionals in the field through the exploration, investigation, and selection of materials and processes. It is possible to examine the most diverse properties of the materials, cost, energy costs, and emission of pollutants in production[5].

Studies have been conducted with the aim of improving the autonomy of electric vehicles in order to make them competitive with vehicles powered through internal combustion. As a result, the efficiency of the electric motors, battery, transmission, the weight of each component, and even intelligent acceleration control profiles are being developed to obtain the best balance between autonomy and performance[3,6,7].

*e-mail: spinelli@ufscar.br

A 10% weight reduction generates an increase in fuel economy of 8 - 10%, therefore automotive industries are looking to reduce the weight of their vehicles[8]. In this context, Al alloys have had wide application and good results due to their low density and suitable properties[9]. Due to this, the use of Al alloys for applications in the automotive industry has increased by more than 80% in the last 5 years. In 1996, for instance, around 110 kg of Al were used in a vehicle while in 2015 consumption reached close to 340 kg[10].

The largest fraction of these materials, especially 300 Al Series alloys, is being applied in the manufacture of engine blocks through casting. Wrought alloys, in turn, have great structural application in vehicle chassis and bodywork. Thanks to the application of Al alloys, the weight reduction of these structures reaches up to 50% in relation to those produced with steels[11].

Wrought alloys have been applied mainly to extruded parts, being welded to other parts to form the final bodywork of electric vehicles. The main alloys used for this application are the 6000 series alloys, due to their suitable properties such as mechanical strength, corrosion resistance, formability, and weldability. In addition, they are hardened via heat treatment and have a good cost-benefit ratio, compared to the 5000 and 7000 alloys, for example[9,11,12].

Considering the chassis structures manufactured with Al alloys[11,13], there are extruded, forged, stamped, and cast parts, all requiring different characteristics and properties. In the case of chassis panels, as they are manufactured from sheets to be stamped, in addition to the basic need for mechanical strength, it is important that they present high formability and high surface quality after pressing and painting finish.

According to Kumar et al.[13], any vehicle's chassis is a crucial component since it provides support for the body and other parts. When constructing a chassis, excessive stress, extreme deflection, and equilateral stress are all crucial factors to take into account. In general, achieving stiff, resistant and lightweight automotive chassis is essential for optimum efficiency.

The 6000 alloys, hardened by phase precipitation (aging) in the painting stage, are the primary choice for these applications. For sheet and extruded structural materials, strength can be a limiting factor in certain applications. Impact energy absorption and high processability in the extrusion process are often important aspects. To meet these requirements, 5000 alloys are primarily used in North America. In Europe, however, the 6000-T4 alloys are still the most widely used[11,12].

As such, the 6000 alloys are good candidates in vehicle structural applications, either as sheet or extruded parts. These alloys are shaped and heat treated, due to the presence of Mg and Si as main alloying elements, which form the reinforcing Mg_2Si phase. The formation of this phase provides the hardening of these alloys proportional to the fraction, distribution, and morphology of the constituting phases. Moreover, the 6000 alloys have found wide applications in welding and structural components due to their excellent corrosion resistance, mechanical strength, and good formability[14,15]. Within this Al alloys series, some specific alloys meet these prerequisites and are constantly tested and applied to manufacture vehicle structural parts. The main alloys for stamping are: 6009, 6010, 6016, and 6111, generally applied as side panels or as the floor of bodies. Moreover, the main alloys applied in the extruded form are: 6061, 6063, 6070, and 6082, generally applied as structural components of vehicles[9,11].

Therefore, the 6000 alloys are the ones that have had the most employment in the studies discussing the use of Al alloys in vehicle chassis, such as the research by Miller et al.[11]. However, despite these alloys being composed of the same alloying elements (i.e., Mg and Si), there is still a variation in composition and properties. Consequently, the present investigation aims to analyze several 6000 alloy types in terms of thermodynamics and properties, producing a comparison and classification between them, using the Thermo-Calc® and the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022. As such, the challenge of this work lies in the correlation of the results obtained by these computations and the selection of the 6000 alloys with the greatest potential for application in electric vehicle chassis in terms of performance, processability, environmental impact, and cost.

2. Methodology

For the comparison of the 6000 alloys in the possible structural application in electric vehicle chassis, thirteen alloys were firstly selected. Eight of them were already mentioned because they can be found in the literature as alloys of interest, that is: 6009, 6010, 6016, 6061, 6063, 6070, 6082, and 6111[9,11]. The other five alloys were the 6005A, 6013, 6022, 6060, and 6066 alloys. The selected alloys were all considered under the T4 and/or T6 heat treatment conditions.

Obtaining results for comparison of these alloys followed four steps. The first step was to determine the maximum composition of each alloy using the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022. Furthermore, the Thermo-Calc® software with the TCAL7 database was used to obtain data on the formation of the phases as well as the variation of the phase fraction as a function of the alloying contents. The second step was the comparison of the alloys based on the mechanical properties considered important for the required application. The analyzed properties were elastic modulus, yield tensile strength, fatigue strength, toughness, density, and corrosion. All data related to the mentioned properties were taken from the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022 using property maps or tables.

The elastic modulus (E), yield tensile strength (σ_y) and density (ρ) were part of the maps that had the function of expressing the adopted performance indices for Al chassis. A performance index means a combination of certain properties of a material that can be used to represent a relation for a particular set of criteria with a particular objective in mind. In the case of the chassis, the calculations were intended to obtain property relationships in order to minimize the part's mass, as indicated by Ashby et al.[16].

The case of the chassis can be approximated to the case of a flat plate, or a panel, constantly suffering bending forces. As such, the following indices must be maximized:

$$M = \frac{E^{\frac{1}{3}}}{\rho} \quad (1)$$

$$M = \frac{\sigma_y^{\frac{1}{2}}}{\rho} \quad (2)$$

Thermo-Calc® result computations were also used in this step to justify the results obtained through the Ashby property maps.

These performance metrics, which include density, yield strength, and elastic modulus, are closely related to the intrinsic properties of alloys. Therefore, a chassis will perform better under loading conditions if its indices are increased by increasing alloy strength and elastic modulus. By lowering density, or raising the indices, the chassis parts will become lighter.

The third step consisted of analyzing data on the processing and welding capacity of the alloys retained as candidates after the first and second steps. This data was acquired in the form of graphs plotted in the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022 with the axis of the ordinates fixed as the alloy prices. As a result, the alloys were compared according to the ability to be processed by cold working, hot working, and stamping. Due to the need to join the manufactured parts, their weldability was also analyzed.

The fourth step was the analysis of the environmental impact of each alloy. In this step, the Eco Audit tool of the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022 was employed. This tool gathered information on energy costs and CO_2 gas emissions in the production and processing of these alloys. Candidate alloys were compared against commercially pure Al. Finally, the averages of the properties and features obtained from the aforementioned steps were summarized for comparison and classification of the alloys under three distinct scenarios: (a) better performance, (b) better processability, and (c) lower environmental impact. Hence, this data allowed to analyze the best alloys in each of the scenarios. As a classification tool, the TOPSIS method[17] was used, scoring each of the alloys in relation to their properties/features and the weights given for each factor in each scenario.

By determining weights for each alloy scenario, normalizing scores for each scenario, and calculating the geometric distance between each alloy and the ideal alloy, which is that with the best score for each scenario, the TOPSIS compensatory aggregation method allow a set of alloys to be compared[17]. A complete description of the scenarios weights will be given later in the Section 4 of this paper.

The flowchart in Figure 1 depicts the whole methodological thought process.

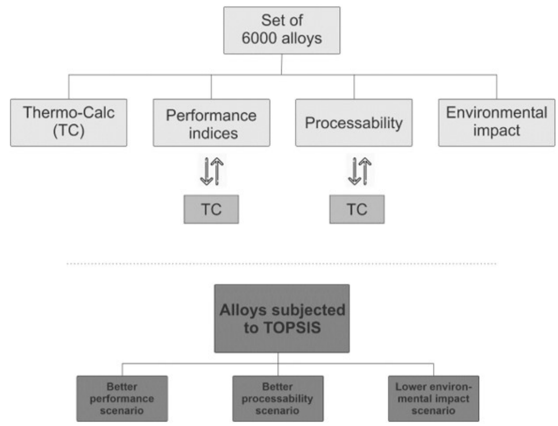

Figure 1. Sequence of computations and analyses completing the methodology for the selection of the 6000 alloys.

3. Results

3.1. Thermo-Calc results

The fundamental difference between the alloys of interest is their chemical composition. Table 1 shows in detail the chemical composition range of each of these alloys. Information on the alloying contents as described in Table 1 was taken from the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022. The main alloying elements are Mg, Si Cu, and Mn, and their contents can change important properties such as mechanical strength, ductility, and toughness. Moreover, they have an impact on the ability of the alloys to be processed, as well as their pricing.

Moreover, thermodynamic calculations associated to the studied alloys were made by using the Thermo-Calc® software. It was possible to quantify the proportion of the phases considering the alloys being processed in equilibrium conditions. It provides better understanding of how much the alloy chemistries may change the microstructure and, consequently, the properties. Table 1 also summarizes the data on the Mg_2Si phase fraction at 600K taken from the software.

According to Table 1, the 6016 and 6060 alloys showed the lowest Mg_2Si fractions, that is 1% and 0.9%, respectively. In contrast, the 6066 and 6010 alloys showed the highest fractions, 2.2% and 2%, respectively. This information is revealing of the possible hardening capacity of the alloys through the aging heat treatment, which consequently influences the properties[12]. The other intermetallics refer to Al_2Cu, AlMnSi and other Fe-bearing: $Al_9Fe_2Si_2$ and $Al_{15}(Fe, Mn)_3Si_2$.

3.2. Performance indices

In order to compare and identify the best alloys for a given application, it is vital to see how changes in chemical composition can result in changes in mechanical properties. Thus, it is possible to identify three important properties initially: Young's modulus (E), yield tensile strength (σ_y) and density (ρ). For this reason, the following property maps were obtained through Ansys® Granta EduPack and Selector displayed as shown in Figure 2. The performance index lines reflecting values defined by Equation 1 and Equation 2 were drawn on the maps.

The performance index lines were placed with a minimum acceptable value in perspective. They were developed using the worst candidate alloy from the literature as a minimum limit in each situation (the 6061-T6 and the 6016-T4 alloys). As a result, the 6066-T6 alloy was eliminated since it had the lowest

Table 1. Compositions and phase fractions characterizing the 6000 alloys examined in this study.

Chemical Compositions (wt.%)									Phase Fractions (mole %)	
Alloys	%Mg	%Si	%Fe	%Cu	%Mn	%Cr	%Others	%Al	Mg_2Si	Other intermetallics
6005A	0.4 - 0.7	0.5 - 0.9	0 - 0.35	0 - 0.3	0 - 0.5	0 - 0.3	0 - 0.45	Bal.	1.2%	-
6009	0.4 - 0.8	0.6 - 1	0 - 0.5	0.15 - 0.6	0.2 - 0.8	0 - 0.1	0 - 0.5	Bal.	1.4%	1.6%
6010	0.8 - 1.2	0.6 - 1	0 - 0.5	0.15 - 0.6	0.2 - 0.8	0 - 0.1	0 - 0.5	Bal.	2.0%	1.0%
6013	0.8 - 1.2	0.6 - 1	0 - 0.5	0.6 - 1.1	0.2 - 0.8	0 - 0.1	0 - 0.5	Bal.	1.7%	1.8%
6016	0.25 - 0.6	1 - 1.5	0 - 0.5	0 - 0.2	0 - 0.2	0 - 0.1	0 - 0.5	Bal.	1.0%	0.2%
6022	0.25 - 0.6	1 - 1.5	0.05 - 0.2	0.01 - 0.11	0.02 - 0.1	0 - 0.1	0 - 0.55	Bal.	1.1%	0.2%
6060	0.35 - 0.6	0.3 - 0.6	0.1 - 0.3	0 - 0.1	0 - 0.1	0 - 0.05	0 - 0.4	Bal.	0.9%	0.1%
6061	0.8 - 1.2	0.4 - 0.8	0 - 0.7	0.15 - 0.4	0 - 0.15	0.04 - 0.3	0 - 0.55	Bal.	1.7%	0.3%
6063	0.45 - 0.9	0.2 - 0.5	0 - 0.35	0 - 0.1	0 - 0.1	0 - 0.1	0 - 0.35	Bal.	1.4%	-
6066	0.8 - 1.4	0.9 - 1.8	0 - 0.5	0.7 - 1.2	0.6 - 1.1	0 - 0.4	0 - 0.6	Bal.	2.2%	2.3%
6070	0.5 - 1.2	1 - 1.7	0 - 0.5	0.15 - 0.4	0.4 - 1	0 - 0.1	0 - 0.4	Bal.	1.9%	2.3%
6082	0.6 - 1.2	0.7 - 1.3	0 - 0.5	0 - 0.1	0.4 - 1	0 - 0.25	0 - 0.45	Bal.	1.9%	2.4%
6111	0.5 – 1	0.6 - 1.1	0 - 0.4	0.5 - 0.9	0.1 - 0.45	0 - 0.1	0 - 0.4	Bal.	1.8%	1.7%

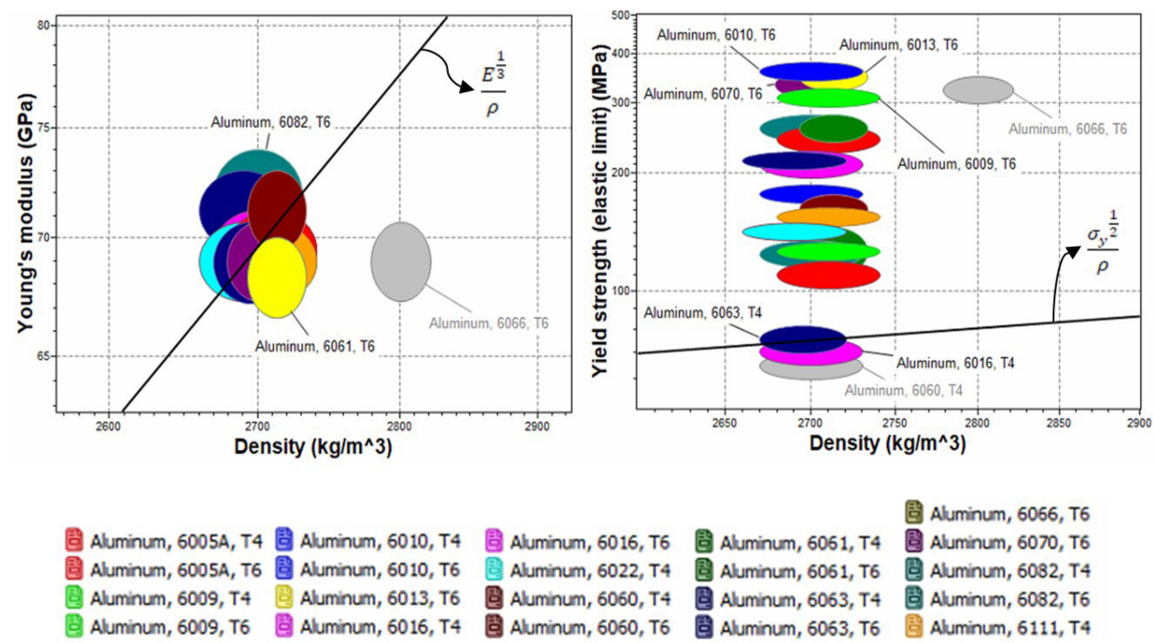

Figure 2. Property maps of the 6000 series alloys with their respective index lines taken from the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022. Images used are courtesy of ANSYS, Inc.

specific stiffness among the the alloys. The 6066-T6 alloy has a larger density than the others, but with a similar Young's modulus. The 6060-T4 alloy, in addition to having a lower alloying content, is subjected to the T4 heat treatment condition, which includes solution followed by natural aging, and hence has the lowest yield strength of all alloys, ranging between 60 and 70 MPa. The very low Mg_2Si fraction of this alloy can be seen in Table 1. The results of its specific calculations using Thermo-Calc® software can be seen in Figure 3.

Since the studied alloys pertain to the same Al series and have a relatively low content of alloying elements, the density does not change very much, with a variation between 2.66 g/cm^3 and 2.74 g/cm^3. Only the 6066 alloy had a higher density than the others, between 2.78 g/cm^3 and 2.83 g/cm^3. This is probably due to the higher content of Cu and Mn as alloying elements, which is not seen in the other alloys. Another interesting factor seen in the maps shown in Figure 2 is that the modulus has a low variation, while the yield strength has a large variation. The yield tensile strength larger variation is probably related to the second phase precipitation optimization in the microstructure from the applied heat treatment. In contrast, the modulus is dependent on the atomic structure of the material.

In parallel to the stiffness and strength, the candidate alloys to be applied in chassis must guarantee the safety of the conductors in all possible situations. In view of this, toughness, fatigue resistance, and corrosion resistance were also analyzed. Figure 4 describes the behavior of the alloys for the cited properties. As demonstrated in Figure 4, the toughness of the alloys has a wide range, from 13 kJ/m^2 to 19 kJ/m^2 (see Figure 4a). The average toughness values of most alloys are close to that of commercially pure Al, of 16 kJ/m^2.

The values for fatigue resistance after 10^7 cycles reveal a wide range. As shown in Figure 4 for the 6010-T6 and 6013-T6 alloys, higher yield strength alloys have a propensity to

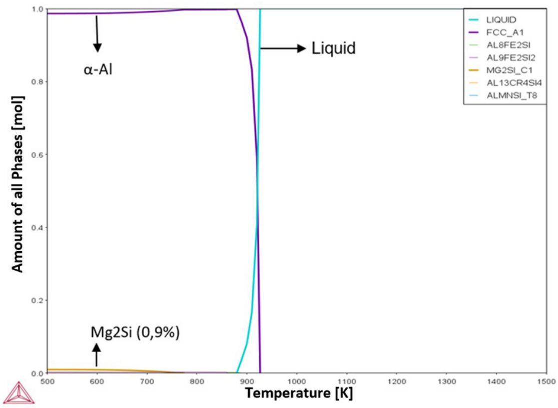

Figure 3. Phase fraction as a function of temperature for the 6060 alloy.

have higher fatigue strength (Figure 4b). However, in some conditions, such as those of the 6070-T6, 6063-T6, and 6060-T6 alloys, this behavior was not observed. Low Cu content appears to induce low fatigue resistance, being responsible for the rise in nucleation of the hardening phase Mg_2Si in the 6000 series alloys[18].

Al alloys usually exhibit excellent corrosion resistance due to a thin oxide layer, called passive layer, which is formed on the surface[19]. One way to analyze the corrosion performance of the 6000 alloys is to measure the material's resistance to stress corrosion cracking, shown in Figure 4(c). Crack growth is caused by the combined effects of stress and chemical attack, where the material to be tested must be exposed in environments that are aggressive and undergo corrosion. According to Figure 4(c), the tested alloys are not vulnerable to stress corrosion even when exposed to a highly corrosive environment (chloride).

3.3. Processability

Another important parameter in comparing these alloys is the material's ability to be processed and formed into the final part for the application. Since this is a qualitative property, Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022 categorizes the materials in four scales: Excellent, where the material is frequently subjected to this type of processing and presents no significant problems;

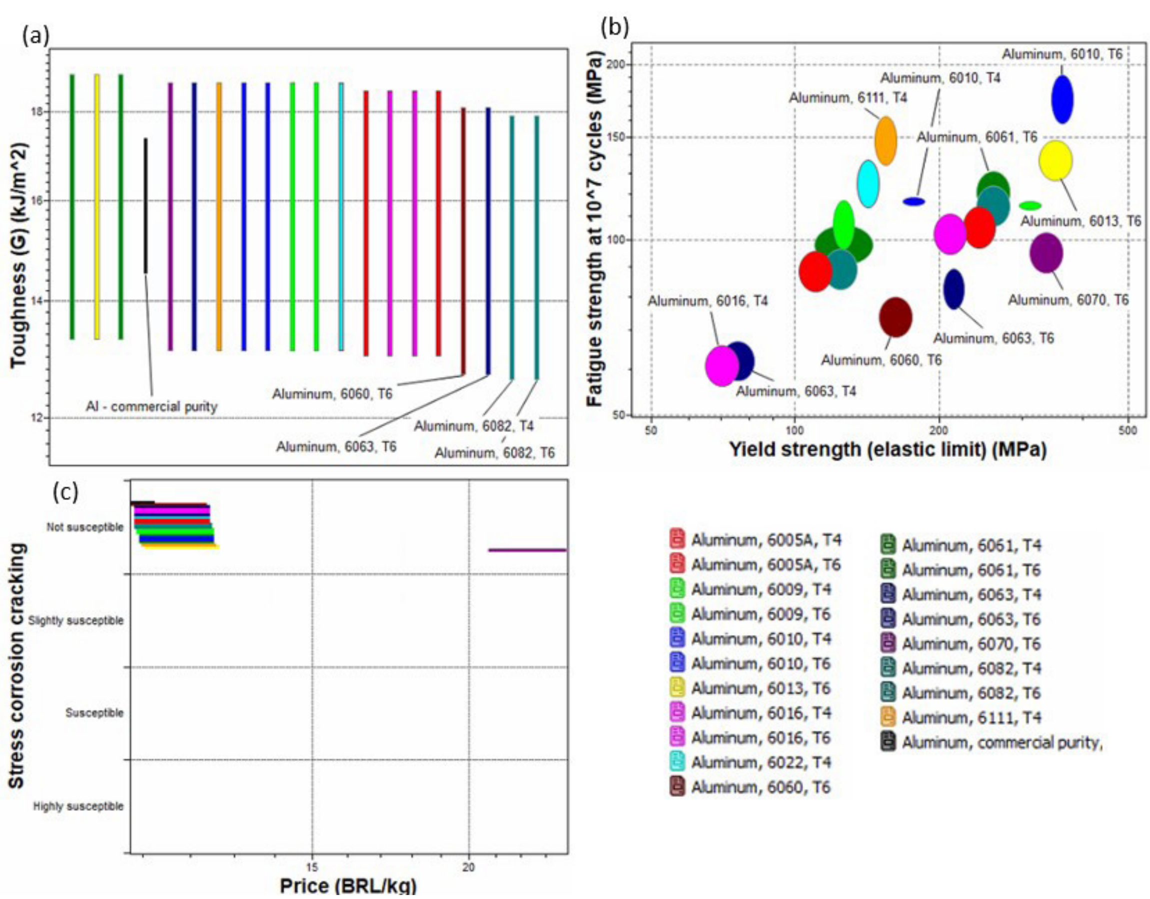

Figure 4. (a) Toughness, (b) fatigue strength, and (c) stress corrosion cracking of the 6000 alloys. Images used are courtesy of ANSYS, Inc.

Acceptable, where the material is generally subjected to this type of processing but is not fully optimized for it; Limited use, where the material can follow this type of processing in limited cases or requires special measures to avoid problems; Inadequate: the material cannot follow this processing.

Figure 5 shows the classification of the candidate alloys in their suitability for cold working and hot working processing. For cold working in Figure 5(a), the 6060-T6, 6061-T4 and 6061-T6 alloys are classified as excellent alloys and have this type of processing optimized. The other candidate alloys are rated in the "acceptable" range. In cold working, a relevant factor for the alloys is their ability to become harder due to plastic deformation, which may have been a decisive factor in the classification of the alloys. For hot working in Figure 5(b), the alloys that are classified as having excellent processability are 6063-T4, 6063-T6, 6061-T4, and 6061-T6. The remaining alloys are rated with acceptable processability. In hot working, one important parameter for comparison is the sensitivity of the material to the strain rate.

Following this path, Figure 6 shows a ranking for the candidate alloys in terms of processability related to pressing or stamping processes and weldability.

For processing by pressing in Figure 6(a), all alloys were rated with acceptable processability, only commercially pure Al as excellent. As for weldability in Figure 6(b), the 6060-T6, 6082-T4, 6082-T6, 6061-T4, and 6061-T6 alloys showed good weldability, while the other alloys showed excellent weldability. Good weldability means that the welded joint

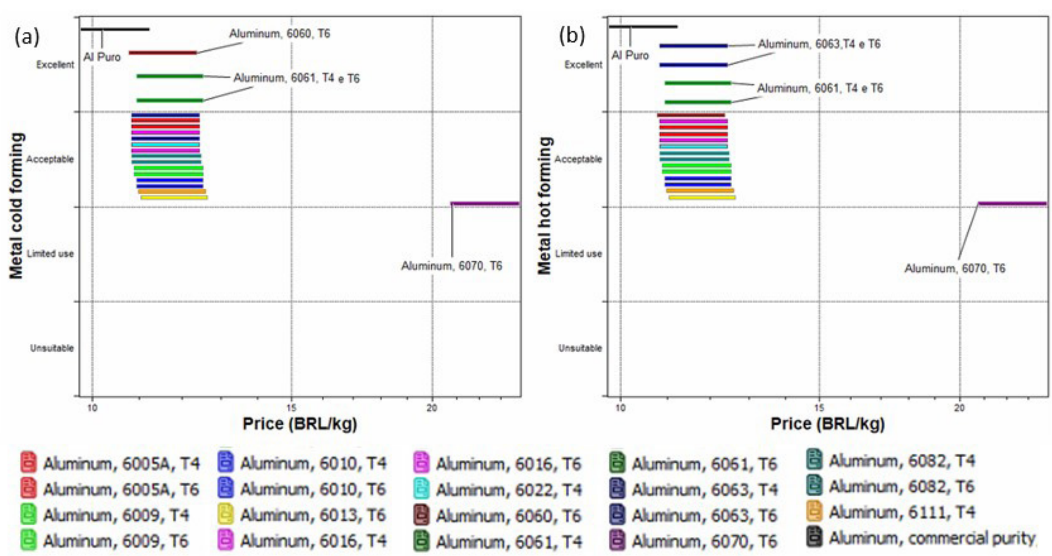

Figure 5. (a) Cold work and (b) hot work processability of the 6000 alloys. Images used are courtesy of ANSYS, Inc.

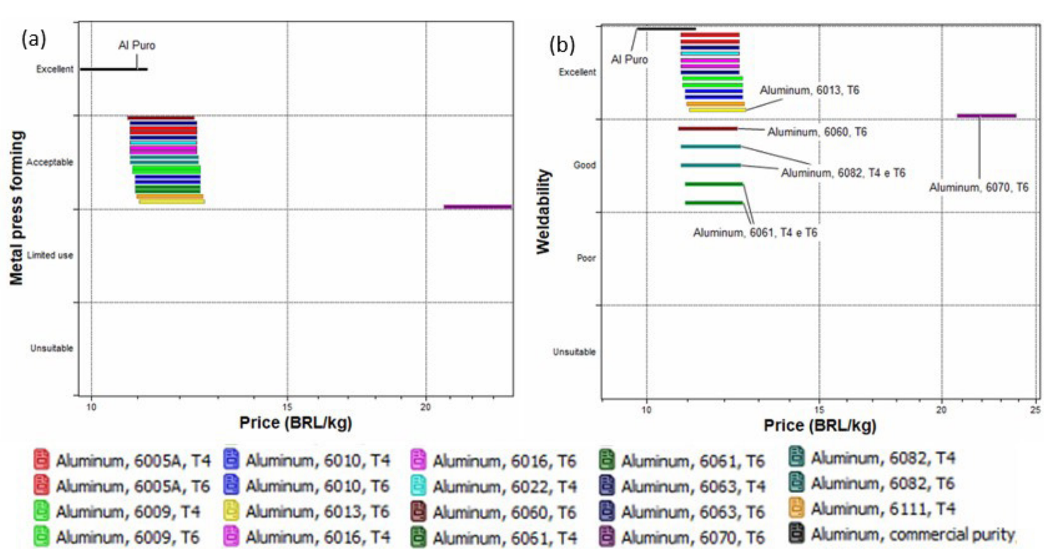

Figure 6. (a) Stampability and (b) weldability of the 6000 alloys. Images used are courtesy of ANSYS, Inc.

achieves acceptable properties. Excellent weldability means that the welded joint achieves optimum properties.

3.4. Environmental impact

The comparison of the candidate alloys in terms of their environmental impact was performed using the Eco Audit tool of the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022. To make this comparison, commercially pure Al was used as the basis for differentiating the energy consumption and carbon dioxide production of all examined alloys. Then, the production and extrusion of 100 kg of each of the alloys were used as a parameter, adopting a typical percentage of recycled material in the material production and recycling the part at the end of the vehicle's life. As a result, both Figure 7 and 8 were generated. Figure 7 shows information regarding the energy expenditure, in (Mega Joules) MJ, while Figure 8 presents information regarding the amount of CO_2 gas emission, in kg. This information includes the production, manufacturing, transportation, use, and disposal of the material. In case of recycling, it also brings the potential future energy savings due to that.

In the graphs shown in Figure 7 and Figure 8, it is seen that the greatest differentiation of energy spent and carbon dioxide emitted is in the production of the material. This is because the T6-treated alloys undergo artificial aging, a treatment that requires a higher energy expenditure. In this heat treatment, the alloys are solubilized and subsequently heated between 100 °C and 200 °C so that the atoms diffuse and precipitation of hardening phases could happen, optimizing the mechanical properties[7,9]. Therefore, this need for a prolonged heating of the parts may generate a higher energy spending than that associated with the production of alloys in T4 condition, which underwent only solubilization treatment, while the aging is carried out at room temperature (naturally).

The alloy characterized by the highest energy expenditure and CO_2 emission was the 6010-T6 alloy, using 13% more energy than the production of commercially pure Al, and emitting 13% more carbon dioxide into the environment.

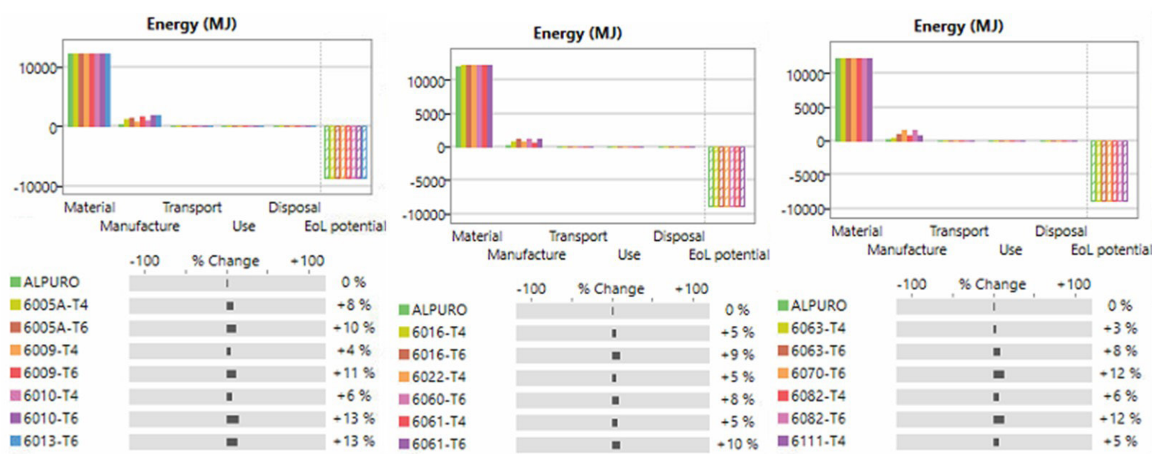

Figure 7. Energy consumption in the production and manufacturing of the 6000 series alloys. Images used are courtesy of ANSYS, Inc.

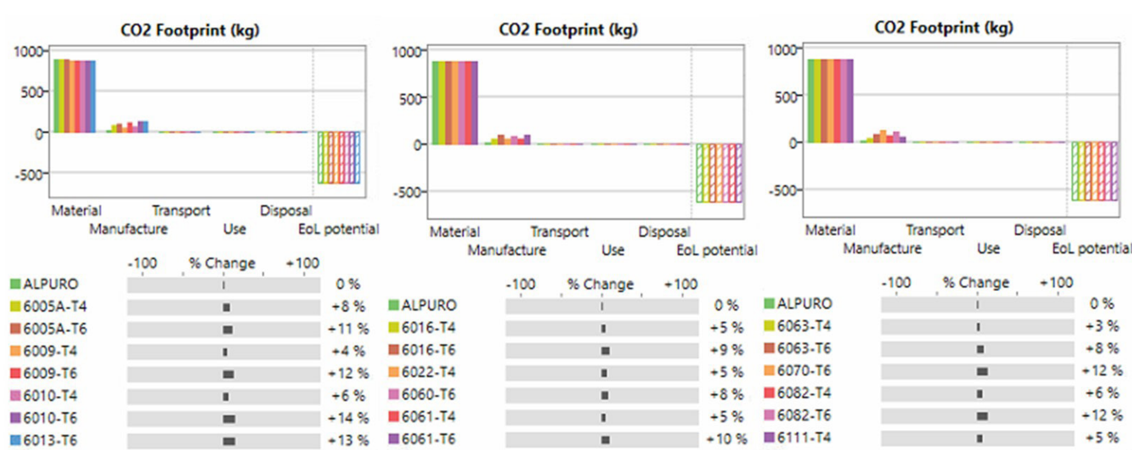

Figure 8. CO_2 footprint in the production and manufacturing of the 6000 series alloys. Images used are courtesy of ANSYS, Inc.

In addition, the alloy with least impactful results on the environment was the 6063-T4 alloy, with energy consumed and carbon dioxide emission only 3% higher than commercially pure Al.

Following the reporting of the major results for 3.2. Performance, 3.3. Processability, and 3.4 Environmental impact, such results will be synthesized and processed using the TOPSIS method of analysis (next item 4). This method will allow for a direct comparison and classification of the alloys confronted with each valence of importance for the referred application, namely the lightweight chassis.

4. Discussions

In order to quantify qualitative properties, such as processability and weldability, scores from one to four were given according to the classification levels in which these properties were categorized by the Ansys® Granta EduPack and Selector software, ANSYS, Inc., 2022, that is: Unsuitable - 1, Poor - 2, Good - 3, Excellent - 4.

Table 2 shows the average properties of all examined 6000 alloys. In addition, three scenarios were considered for comparison, one aiming at better performance, another aiming at better processability, and the last one aiming at the lower environmental impact.

The weighting for performance was defined giving higher percentage for the performance index related to the Young's modulus. 70% was defined for properties divided into 28% for MI_1, 14% for MI_2, 14% for toughness and 14% for fatigue. Processing, environmental impact and cost were pondered in 10% each. A summary of the three scenarios weights in detail can be seen in Figure 9.

As shown in Figure 10(a) the 6010-T6 alloy was the highest ranked in the performance scenario probably due to its high content of alloying elements, thus being the alloy with the best mechanical properties. As expected, the alloys under T6 condition dominated the top of the ranking in this scenario due to the benefits of the artificial aging heat treatment. The highest ranked alloys related to the T4 condition was the 6111-T4 alloy.

For the processability scenario, the weighting was based on 60% for processability characteristics. More weight was devoted to these criteria for the alloys' ability to undergo hot deformation and weldability. The highest ranked alloy in the processability scenario was the 6061-T4 alloy, followed by the 6111-T4 alloy. Only the worst ranked three alloys, the 6082-T4, 6082-T6, and 6070-T6, were further apart in relation to the other evaluated alloys, as can be seen in Figure 10(b).

The weighting for the environmental impact scenario was elaborated giving greater weight to the aspects related to energy (30%) and CO_2 emission (30%). The score variance in this scenario was higher than in the prior two situations. This demonstrated that despite these alloys are from the same Al series and have comparable compositions, the alloys' manufacturing and processing methods have a significant influence on the environmental impact of production. The T4 condition alloys were better classified than the T6 condition alloys. This is because the T6 heat treatment requires more energy. As a consequence, the 6009-T4 alloy was the highest ranked, closely followed by the 6063-T4 alloy. For this scenario, the 6111-T4 alloy, which was the best alloy in the T4 condition in terms of performance, was classified as third.

Table 2. Summary of the property values of the 6000 alloys.

Alloys	MI_1 - $\frac{E^{\frac{1}{3}}}{\rho}$	MI_2 - $\frac{\sigma_y^{\frac{1}{2}}}{\rho}$	Toughness (kJ/m²)	Fatigue Strength (10^7 cycles) (MPa)	Processability	Weldability	Energy (%)	CO_2 footprint (%)	Cost (US$/kg)
6005A-T4	1.52	3.88	15.8	88.7	3	4	8	8	2.28
6005A-T6	1.52	5.76	15.8	105.7	3	4	10	11	2.28
6009-T4	1.51	4.14	15.9	107	3	4	4	3	2.30
6009-T6	1.51	6.50	15.9	115	3	4	11	12	2.30
6010-T4	1.52	4.93	15.9	117	3	4	6	6	2.30
6010-T6	1.52	7.05	15.9	175.5	3	4	13	14	2.30
6013-T6	1.51	6.91	16.1	137.5	3	4	13	13	2.34
6016-T4	1.52	3.11	15.8	61.1	3	4	5	5	2.28
6016-T6	1.52	5.38	15.8	102.9	3	4	9	9	2.28
6022-T4	1.52	4.43	15.9	125.5	3	4	5	5	2.28
6060-T6	1.53	4.70	15.4	74.1	4	3	8	8	2.28
6061-T4	1.51	4.17	16.1	98.6	4	3	5	5	2.30
6061-T6	1.51	5.95	16.1	121.5	4	3	10	10	2.30
6063-T4	1.52	3.23	15.9	62.3	3	4	3	3	2.28
6063-T6	1.54	5.45	15.4	82.9	3	4	8	6	2.28
6070-T6	1.52	6.79	15.9	95.5	3	4	12	12	4.39
6082-T4	1.54	4.13	15.3	89.6	3	3	6	6	2.28
6082-T6	1.54	5.97	15.3	115	3	3	12	12	2.28
6111-T4	1.51	4.59	15.9	149	3	4	5	5	2.32

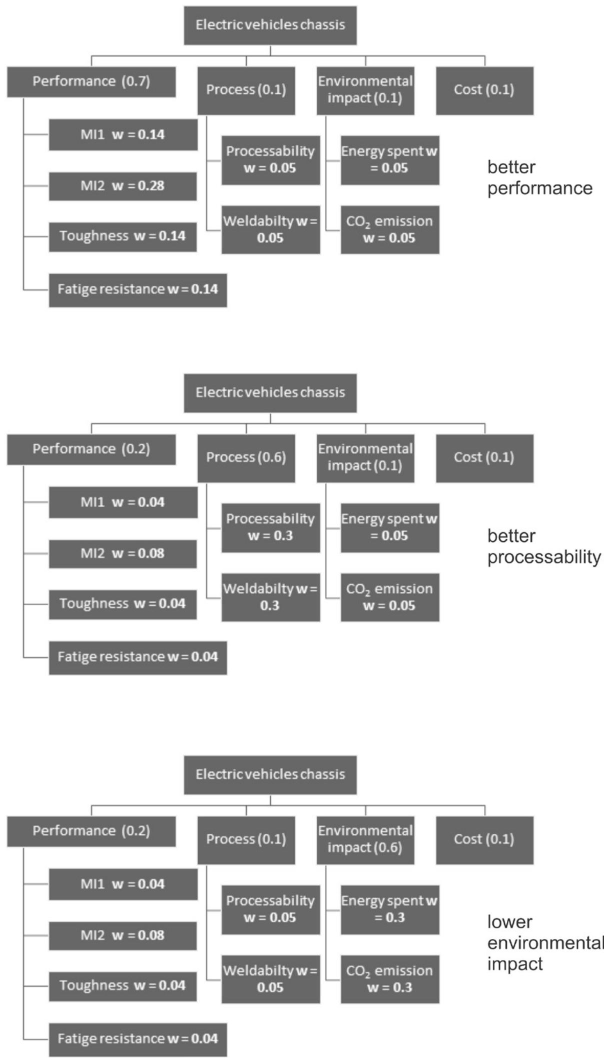

Figure 9. Criteria weights (w) employed for examining the candidate Al alloys for chassis.

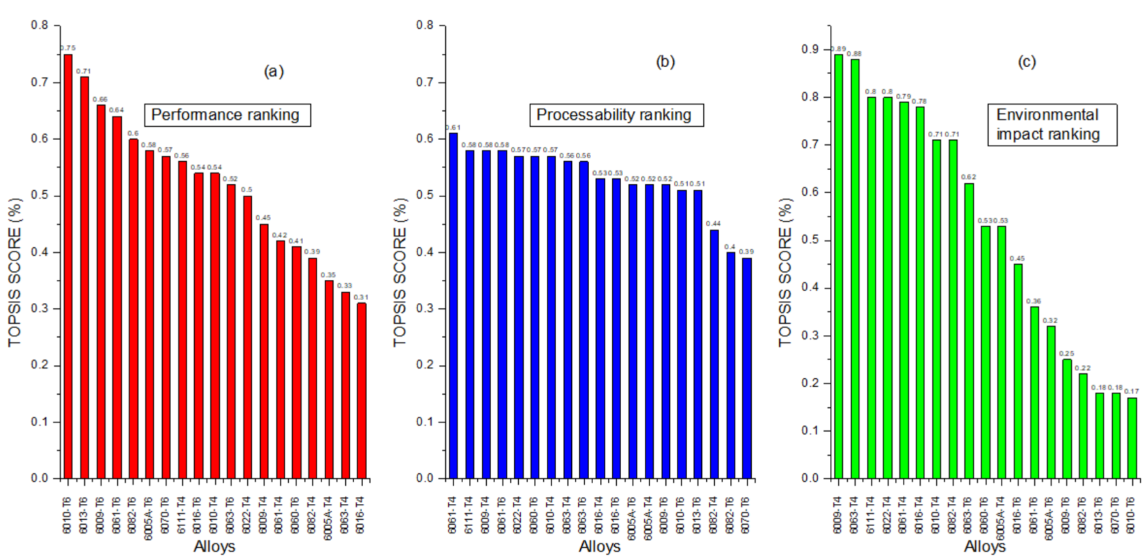

Figure 10. 6000 alloy rankings for the 3 planned scenarios through TOPSIS: (a) performance, (b) processability and (c) environmental impact.

5. Conclusions

The current investigation leads to the following conclusions:

- If the performance is considered, the T6-temper alloys showed the best scores, with the 6010-T6 alloy being the highest ranked alloy. It is worth mentioning that the 6111-T4 alloy was the best ranked among the T4 temper, ranking eighth overall and ahead some T6 temper alloys.
- When processing is prioritized, the TOPSIS score variance across the alloys was not significant, with the 6061-T4 alloy taking the first position, followed by the 6111-T4 and 6009-T4 alloys.
- For the scenario of lower environmental impact, it is noticeable that the T4 temper alloys produced the lowest environmental impact in relation to the T6. Therefore, the 6009-T4 alloy was ranked first, followed by the 6063-T4, 6111-T4 and 6022-T4 alloys. The Eco-Audit tool is a simplified life cycle analysis tool (streamlined LCA). The results obtained from this work are generally satisfactory, indicating that the most important steps are extraction and manufacture, which is coherent since the T4 heat treatment impacts less than T6. However, if a more in-depth analysis of this criterion is required, it is recommended that a more complete LCA tool be used.
- In a broader sense, the 6111-T4 alloy received favorable results in all three evaluated topics. Despite not leading any of the proposed scenarios, it was the second best regarding to the processability and the best T4 temper alloy when evaluating the performance scenario. Furthermore, it came in the third place in the most crucial scenario for electric vehicles, the one emphasizing the least environmental effect.

6. Acknowledgments

The authors are grateful to CNPq - National Council for Scientific and Technological Development, Brazil (grant # 308931/2019-0), to FAPESP - São Paulo Research Foundation, Brazil (grant: #2019/23673-7) and to CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil - Finance Code 001 for their financial support.

The authors are grateful to Ansys, Inc for allowing the use of Ansys Granta EduPack and Selector software, ANSYS, Inc., 2022 on this paper. This work was developed using the Granta EduPack and Selector.

7. References

1. Lasi H, Fettke P, Kemper HG, Feld T, Hoffmann M. Industry 4.0. Bus Inf Syst Eng. 2014;6(4):239-42.
2. Lin D, Lee CKM, Lau H, Yang Y. Strategic response to Industry 4.0: an empirical investigation on the Chinese automotive industry. Ind Manage Data Syst. 2018;118:589-605.
3. Wang Z, Ching TW, Huang S, Wang H, Xu T. Challenges faced by electric vehicle motors and their solutions. IEEE Access. 2021;9:5228-49.
4. ThermoCalc. About Themo-Calc Software [Internet]. 2020 [cited 2020 Feb 28]. Available from: https://thermocalc.com/.
5. Ansys. Support for Materials Education [Internet]. 2022 [cited 2022 Feb 23]. Available from: https://www.ansys.com/products/materials/granta-EduPack.
6. Li J, Jiao J, Tang Y. An evolutionary analysis on the effect of government policies on electric vehicle diffusion in complex network. Energy Policy. 2019;129:1-12.
7. Luque P, Mántaras DA, Maradona Á, Roces J, Sánchez L, Castejón L et al. Multi-objective evolutionary design of an electric vehicle chassis. Sensors. 2020;20:3633.
8. Morita A. Aluminum alloys for automobile applications. In: ICAA 6th; Aichi, Japan. Proceedings. Tokyo: The Japan Institute of Light Metals; 1998. p. 25-32.
9. Mallick PK. Materials, design and manufacturing for lightweight vehicles. 2nd ed. Duxford: Woodhead Publishing; 2020.
10. Sears K. Automotive engineering: strategic overview. Steel World. 1997;2:55-68.
11. Miller WS, Zhuang L, Bottema J, Wittebrood AJ, De Smet P, Haszler A et al. Recent development in aluminium alloys for the automotive industry. Mater Sci Eng A. 2000;280(1):37-49.
12. Chandla NK, Kant S, Goud MM. Mechanical, tribological and microstructural characterization of stir cast Al-6061 metal/matrix composites-a comprehensive review. Sadhana. 2021;46:47.
13. Kumar S, Girgoswami R, Shukla A, Shinde P, Rathod NT. Design and analysis of chassis for electric vehicle. IRJET. 2021;8:3195-9.
14. Prakash YMS, Shankar MCG, Karthik X, Sharma SS, Kini A. Property enhancement during artificial aging of Al6061-silicon oxide metal matrix composites. Mater Today Proc. 2018;5(11):24186-93.
15. Lee SH, Saito Y, Sakai T, Utsunomiya H. Microstructures and mechanical properties of 6061 aluminum alloy processed by accumulative roll-bonding. Mater Sci Eng. 2002;325(1-2):228-35.
16. Ashby MF, Shercliff H, Cebon D. Materials: engineering, science, processing and design. 4th ed. Oxford: Butterworth-Heinemann; 2019.
17. Jee DH, Kang KJ. A method for optimal material selection aided with decision making theory. Mater Des. 2000;21:199-206.
18. Esmaeili S, Lloyd DJ. The role of copper in the precipitation kinetics of 6000 series al alloys. Mater Sci Forum. 2006;519-521:169-76.
19. Reboul MC, Baroux B. Metallurgical aspects of corrosion resistance of aluminium alloys. Mater Corros. 2011;62:215-33.