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Technical Considerations on the Development of Grounding Terminals for Automotive Applications

Sophia Lirio Nunes Santos, Geraldo Creci*

Instituto Federal de São Paulo – Campus Bragança Paulista, SP, Brasil
*Corresponding author - E-mail: gcreci@ifsp.edu.br

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***Abstract*—*This work presents important technical considerations regarding the development of grounding terminals for automotive applications. Aspects involving the electrical architecture of vehicles are considered for the development of grounding terminals, since the integrity of the electrical system is critical for performance, safety, and reliability. Relevant concepts about the project development flow are presented, as well as strategies for preventing the formation of whiskers, which can lead to failures. Furthermore, the main tests required by standards are described in order to provide a more comprehensive and applied approach to the factors that ensure the conformity, efficiency, and robustness of grounding terminals for automotive applications. Thus, it is expected that the content presented here will serve as a basis for the development of safer, more reliable automotive grounding terminals aligned with the demands of new technologies currently found nowadays.*

I. INTRODUCTION

The world's largest automotive market, China, is committed to promoting the development of alternative vehicles to reduce oil consumption and imports (Xiong et. al., 2019). In Europe, Germany had pledged to increase the operation of electric vehicles to reduce CO2 emissions (Massiani, 2015), while France and the United Kingdom plan to discontinue the sale of conventional vehicles by 2040 (Li et al., 2019).

In this context, grounding stands out as a crucial component to ensure the safety, performance, and reliability of automotive electrical systems. The grounding terminal, responsible for establishing the connection between the grounding systems and the metallic parts of the vehicle, plays an essential role in protecting against electrical faults, dissipating voltage spikes, and reducing electromagnetic interference. The design of grounding terminals faces significant technical challenges, especially when considering the voltage variations present in vehicles, which can range from 12V in low-power systems to up to 400V in high-power systems, such as those found in fully electric vehicles and hybrid vehicles.

The design of these terminals requires an analysis of characteristics such as contact strength, which ensures a firm and efficient connection, material finishing, which influences resistance to corrosion and wear, and the stress relaxation phenomenon, which can compromise the integrity of the terminal over time. In an increasingly demanding automotive market, the development of an efficient grounding terminal is fundamental to ensuring the integrity of the electrical system and, consequently, the safety of users and the reliability of vehicles.

In high-performance engineering applications, many physical phenomena can be important and should be considered through analytical, numerical, and experimental analyses (Creci, 2021; dos Santos et. al., 2022; Lino et. al., 2023). Stress relaxation can be defined as the gradual reduction of internal stress in a material subjected to constant deformation over time, due to creep and microstructural rearrangement, resulting in loss of contact force in electrical connections. This phenomenon is particularly relevant in metallic alloys used in automotive terminals, as it can directly affect the mechanical and electrical stability of the joint, especially under conditions of high temperature and vibration. Figure 1 shows an illustrative example of an automotive grounding terminal.

Fig. 1: Illustration of an automotive grounding terminal.

Contact resistance can be influenced by factors such as surface roughness, contact pressure, the presence of oxides and contaminants, as well as the properties of the materials used. Contact force plays an essential role in this process, as it is responsible for breaking through layers of oxides and surface impurities, allowing the establishment of a real area of efficient conductor-conductor contact for the passage of electric current. In automotive applications, especially in grounding systems and power connections, the contact force must be sufficient to ensure low resistance and mechanical stability. It is recommended that the contact resistance in critical automotive connections be less than 5 mΩ per metallic junction, a value that ensures minimal voltage drop, avoids local heating, and preserves the electrical and mechanical integrity of the system throughout the vehicle's service life.

Grounding in general electrical systems provides a low-resistance path for leakage currents, lightning strikes, or internal faults to be diverted to the ground, reducing the risk of shocks and damage. In addition, the grounding system must keep the potentials of the metallic parts close to the ground potential, preventing dangerous voltage differences.

The choice of grounding points is determined by several aspects, such as ease of installation and inspection, protection against corrosion and vibration, proximity to the component to be grounded, and compliance with standards requirements. Passenger vehicles typically have 10 to 20 grounding points distributed among the engine, chassis, and electronic modules; this number may be even higher in hybrid and electric vehicles due to the complexity of their high-voltage systems. Table 1 lists the most common grounding locations in a typical passenger vehicle manufactured nowadays.

Table 1: Most common grounding locations in a typical passenger vehicle.

Battery module	Connection between the metal battery casing and the chassis.
Powertrain and control unit	Grounding of chassis and inverters, DC converters and on-board chargers.
Body structure	Interconnection points between different metal sections of the vehicle body, ensuring electrical continuity.
Electric traction motor	The terminal is usually mounted on the motor flange and its function is to drain leakage currents.
Instrument panel and electronic modules	Grounding of electronic control units, communication modules, and sensors; Important for reducing noise and interference in communication systems.
Charging system	Connection between the external charging point and the vehicle's grounding system. Essential for protection against shocks during charging.

Therefore, the development of a grounding terminal must consider not only the properties of the terminal itself, but also the specific characteristics of each region where it will be applied, ensuring greater robustness and reliability for the connection. The main standards applicable to automotive grounding systems are presented in Table 2.

II. DESIGN AND MANUFACTURING PHILOSOPHY

The development of an automotive grounding terminal generally begins with the identification of a market need or the emergence of a technological trend. This stage is conducted by the product management team, which can act both reactively, responding to specific customer requests, and proactively, through market analysis and industry benchmarking.

Once the demand is established, different functional areas of the company are involved in a structured way. The cost and purchasing team is called upon to gather quotes for raw materials and components, enabling a preliminary estimate of economic viability. In parallel, the process team evaluates the necessary manufacturing methods, defining production technologies, tools, and any investments in equipment.

Table 2: Main standards applicable to automotive grounding systems.

USCAR-21	A standard widely adopted by automakers and suppliers in the automotive sector, developed by the United States Council for Automotive Research consortium. Its main objective is to establish minimum technical requirements to guarantee the electrical and mechanical performance of crimped connections between metal terminals and electrical conductors in automotive vehicles.
IEC 60364	This standard establishes requirements for grounding systems and protection against electric shock in low-voltage installations. It defines minimum earth resistance values, equipotential bonding methods, and safety criteria, ensuring the protection of people and equipment against electrical faults. It is widely used as an international reference for safe grounding practices in various applications, including automotive.
ISO 19642	A series of standards that addresses electrical cables for road vehicles, covering everything from dimensional requirements to mechanical, thermal, and electrical testing. It focuses on standardization for low and high voltage cables, ensuring consistent performance under different environmental and operating conditions.
ISO 6469	This standard defines insulation resistance limits, procedures for protection against electric shock, and guidelines to ensure the safe connection of conductive parts to a grounding point, in order to avoid potential risks to vehicle passengers.
ISO 16750	This standard addresses the environmental conditions and tests applicable to electrical and electronic equipment in road vehicles. For the grounding terminal, this standard is fundamental for determining resistance tests to vibration, mechanical shock, thermal exposure, dust, humidity, and corrosive substances. Applying this standard ensures that the terminal maintains its electrical and mechanical properties under different operating conditions.
SAE J1742	This standard specifies the requirements and test methods for high-voltage cables and connectors used in electric and hybrid vehicles. It covers aspects such as insulation, electrical resistance, thermal performance, and compatibility with automotive fluids, ensuring safety and reliability in systems up to 1000 V DC.
SAE J1128	Defines the requirements for low-voltage electrical cables, up to 60 V DC or 25 V AC, used in vehicle wiring. Specifies the main construction, insulation, and performance characteristics to ensure safety and durability in standard automotive applications.
SAE J1127	This standard specifies battery cables for motor vehicles that operate at nominal voltages up to 60 V DC. It addresses diameters, materials, mechanical and thermal resistance, aiming to withstand high currents and severe operating conditions.

The quality team plays an essential role in conducting risk analysis, considering histories of non-conformities and lessons learned from previous projects. Simultaneously, the product engineering team works on developing the initial concept and design, seeking to align technical, regulatory, and performance requirements with cost and schedule expectations. Regarding technical requirements, it is important to emphasize that for each client and each application since there are specific requirements that must be rigorously observed. In the automotive sector, each automaker adopts its own technical standards and norms, which guide the development and validation of components.

During the conception and design phase, it is common practice to continuously consult specific standards and guidelines, ensuring that the grounding terminal is developed in accordance with the performance, safety, and reliability requirements established by the clients. Specific standards cover aspects such as electrical contact resistance, current carrying capacity, mechanical integrity after crimping, corrosion resistance, and behavior under vibration and temperature-critical parameters for product approval and certification.

Strict adherence to these standards is essential for the grounding terminal to meet the validation criteria required by automakers, avoiding rework and rejections during the qualification stages. In this way, technical development is not limited to the creation of a new component, but also to full compliance with normative specifications that guarantee the compatibility and reliability of the product in the automotive environment.

The project team, in turn, is responsible for developing the detailed schedule, including technical and administrative milestones, as well as conducting product development from conception to the start of mass production. This role ensures integration between the different areas involved and promotes continuous monitoring of progress, ensuring that deadlines and goals are met. Only after consolidating these marketing, technical, process, quality, cost, and project management analyses is it possible to obtain a more robust definition of the grounding terminal's viability and establish its final cost. This multidisciplinary flow ensures that design decisions are made in an integrated manner, reducing risks and increasing the product's competitiveness in the automotive sector.

The manufacturing process of a grounding terminal involves several stages, with stamping being one of the main ones. Stamping is a metallurgical technique widely used in metallic materials, which uses a press with a die to perform the necessary cutting, bending, and drawing steps. These steps shape the metal sheet into specific forms, ensuring high precision and repeatability. For grounding terminals, progressive dies are commonly used, which are tools composed of several workstations arranged sequentially, see Figure 2. As the raw material tape advances through the workstations, different cutting and bending operations occur until the terminal reaches its final geometry.

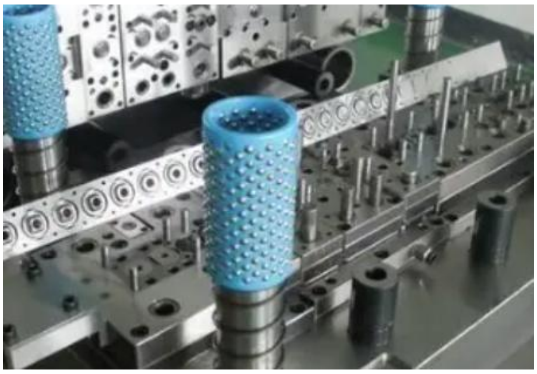

Fig. 2: Illustration of a progressive die for stamping.

Another important step in the manufacturing process, electroplating, refers to a fundamental electrochemical process in the manufacture of grounding terminals, whose main objective is to apply metallic coatings that provide protection against corrosion, improve solderability, and ensure greater durability of the components. The drum electroplating process is widely used for small parts in large volumes, where there is no need to hang them individually, see Figure 3. Providing suitable coatings to the terminals can contribute to achieving better resistance, durability, and electrical performance properties in challenging usage situations.

Fig. 3: Illustration of a drum electroplating machine.

III. WHISKERS PREVENTION STRATEGIES

Microscopic crystalline filaments, known as whiskers, can spontaneously develop on metallic surfaces subjected to internal residual stresses (George and Pecht, 2014). These stresses originate from various industrial processes, including electroplating, differences in coefficients of thermal expansion between metallic layers, and also mechanical forming steps, such as stamping and bending, which introduce compressive residual stresses in the metallic coating, favoring the growth of whiskers. Table 3 presents the main raw materials and finishing used in the manufacture of automotive grounding terminals.

Table 3: Main raw materials and finishing used in automotive grounding terminals.

Raw Material / Finishing	Tin (Sn)	Tin on Nickel (Sn/Ni)	Silver (Ag)	Gold (Au)
Electrolytic Copper (Cu ≥ 99.9%) Conductivity: ~100% IACS	5–10 µm	Sn 5–10 µm on Ni 1–3 µm	2–5 µm	0,1–0,5 µm
Brass (Cu-Zn) Conductivity:25–35% IACS	5–10 µm	Sn 5–10 µm on Ni 1–3 µm	practically not applied	practically not applied

Bronze (Cu-Sn) Conductivity: 15–20% IACS	5–10 µm	Sn 5–10 µm on Ni 1–3 µm	specific cases	not applied
Aluminum Conductivity: ~60% IACS	8–15 µm	Sn 8–15 µm on Ni 1–2 µm	specific cases	practically not applied

Whisker formation occurs as a mechanism for relieving internal stresses accumulated in the tin plating. These filaments, illustrated in Figure 4(a) can grow to a size sufficient to establish short circuits between adjacent conductive tracks or grounded surfaces, potentially causing failures. Figure 4(b) compares human hair with a metallic whisker.

Key preventative measures include the use of tin alloys containing small percentages of lead (when permitted by environmental regulations), the application of nickel barrier layers between the base metal and the tin plating, and rigorous control of the material's electroplating parameters. It is also recommended conducting accelerated aging tests to verify dimensional stability and the propensity for whisker formation throughout the component's lifespan.

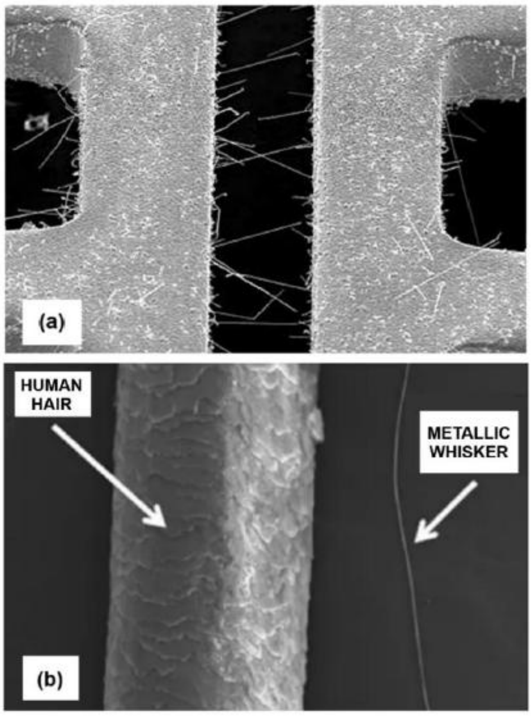

Fig. 4: (a) Illustration of whiskers growth; (b) Comparison between tin whisker and human hair.

IV. MAIN STANDARDIZED VALIDATION TESTS

In the development of a grounding terminal, some essential requirements are necessary for good performance, such as: high electrical conductivity; mechanical resistance, since vehicles are subject to vibration, impacts and temperature variations; corrosion resistance, as the automotive environment is aggressive to metallic components due to exposure to humidity, salinity, chemical agents and thermal variations; and, ease of assembly and inspection in future preventive or corrective maintenance.

Cross-Sectional Analysis Test

It allows for the evaluation of the uniform distribution of the conductor and the correct penetration of the wings over the insulation, ensuring low contact resistance and mechanical integrity. Defects such as internal voids or excessive compression can generate increased resistance or localized hot spots. Figure 5 shows examples of cross-sections with minimum, nominal and maximum crimping.

Accelerated Environmental Exposure Test (ENV)

It simulates accelerated degradation due to oxidation, humidity, and chemical agents. Increased contact resistance or oxide formation can compromise electrical conductivity and promote intermittent failures. During ENV tests, the component is subjected to controlled temperature and humidity cycles in climatic chambers, and may also be exposed to salt spray or aggressive chemical agents such as oils and fuels, (LeBozec et. al. 2008). Figure 6 illustrates automotive grounding terminals with and without corrosion.

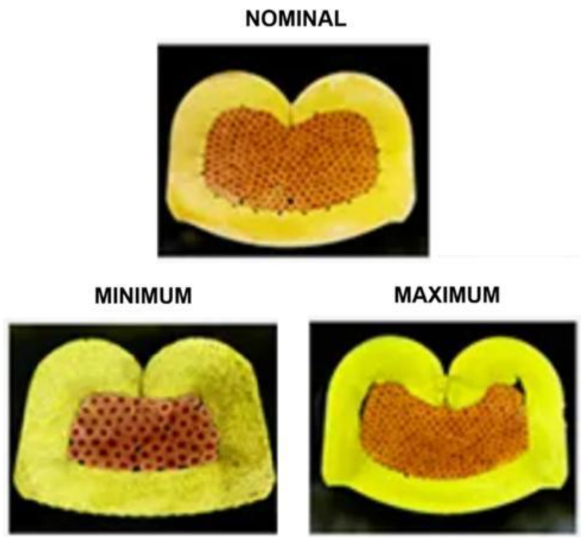

Fig. 5: Examples of cross-sections with minimum, nominal and maximum crimping.

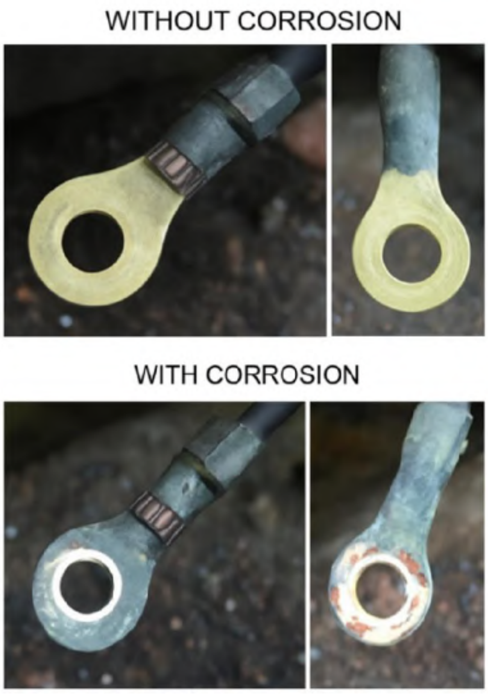

Fig. 6: Illustration of automotive grounding terminals with and without corrosion.

Maximum Current Rating Test

The maximum current rating test provides thermal limits for safe current conduction. Exceeding the maximum operating temperature can reduce the mechanical hardness of the terminal and promote wigns relaxation, decreasing contact pressure. The purpose of the maximum rated current test is to determine the maximum electrical current that a terminal-conductor assembly can safely conduct without exceeding the temperature limits specified for the component or system. This is a thermal characterization procedure, mainly used to generate so-called derating curves, which indicate the reduction in current carrying capacity as the ambient temperature increases.

1008-hour Current Cycling Test

It reproduces cyclic thermal expansions and contractions, evaluating crimp stability and maintenance of electrical resistance. The analysis allows for the prediction of degradation due to thermal fatigue and localized oxidation. The 1008-hour current cycling test is widely used in the validation of electrical terminals, especially in automotive and industrial applications, with the aim of evaluating electrical stability and mechanical durability over time. This procedure is described in international standards and can be adapted according to the technical requirements of each manufacturer.

Conductor-Terminal Pull Force Test

The conductor-terminal pull force test ensures that the crimping of the wire and terminal is secure, reliable, and capable of withstanding mechanical stress. The objective is to measure the force required to pull the conductor out of the terminal after crimping, verifying that it was performed correctly and that the electrical contact is mechanically secure, see Figure 7. Thus, it is possible to ensure that the crimping withstands tensile or vibrational mechanical stresses. Slip failures indicate insufficient compression, while conductor breakage suggests excessive mechanical deformation, indicating that the crimping was too strong and may have damaged the wires.

The integration of these tests offers a comprehensive view of the expected behavior of the terminals in real operation, ensuring electrical reliability, thermal stability, and mechanical strength throughout the system's lifespan. Table 4 presents the main parameters evaluated, typical limits and values for the main tests standardized validation tests presented in this paper.

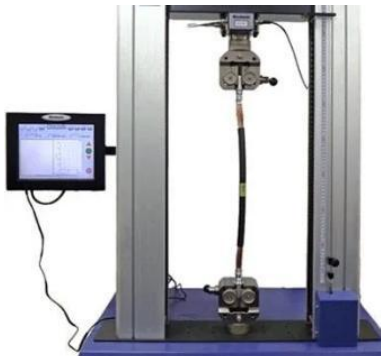

Fig. 7: Illustration of conductor-terminal pull force test.

Table 4: Parameters evaluated and typical values for the tests presented in this paper.

Test	Parameters	Limits / Typical
Cross-Sectional Analysis	Conductor compaction, crimp centering and wings penetration.	75–90% fill, no broken wires and centered crimping.
Accelerated Environmental Exposure (ENV)	Contact resistance, coating degradation and corrosion.	Stable resistance and without significant corrosion.
Maximum Current Rating	Temperature rise and current capacity.	Maximum temperature within limits, and safe

1008-hour Current Cycling	Contact resistance, voltage drop and temperature rise.	R ≤ 20 mΩ; V ≤ 20 mV; ΔT ≤ 55 °C.
Conductor-Terminal Pull Force	Axial force required to detach the conductor and type of fault.	Wires do not slip and no breakage or damage.

V. CONCLUSIONS

The analysis of typical test results applied to automotive grounding terminals can only be fully understood when contextualized within the actual component development workflow. The observed performance, whether in electrical, mechanical, or thermal terms, reflects decisions made in earlier stages of the project, from the choice of material and coating to the definition of crimping geometry and manufacturing parameters. Critical phenomena, such as the growth of metallic whiskers, can only be predicted or mitigated when development considers microstructural factors and surface treatment processes. Without this integrated knowledge, the interpretation of test results would be limited and could lead to incomplete or incorrect conclusions about the terminal's reliability. Therefore, results analysis is not merely the observation of isolated numbers or parameters.

This integrated view reinforces the importance of structured development, showing that tests and technical analyses are essential tools, but their value depends on the quality and rigor of the development workflow that precedes them. Thus, the actual development workflow acts as an interpretive lens for the results obtained. It allows for connecting causes and effects, assessing risks, and establishing criteria for continuous improvement, ensuring that automotive grounding terminals meet the quality and performance standards required nowadays.

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