



Application of a Slide Hammer with a Magnetic Return Mechanism in Cold Glue PDR Technology: A Comparative Analysis and Features of Working with Aluminum Body Panels

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Abstract

This article examines the specific features of applying Paintless Dent Repair (PDR) technology to aluminum body panels under conditions of increasing use of lightweight structural materials and the growing volume of insurance-related repairs associated with local damage without coating disruption. The study combines a systematic review of scientific publications with the development of an original contact-mechanical interpretation of the PDR process focused on the stability of impulse transmission under conditions of limited aluminum plasticity. The analysis addresses the mechanics of localized aluminum deformation, adhesion interactions, friction processes, and the deformation behavior of sheet materials during localized pulling operations. Particular attention is given to the theoretical reinterpretation of PDR as a controlled cyclic system of impulse–traction loading transmitted through an adhesive interface. In contrast to conventional approaches that primarily associate repair efficiency with the magnitude of the applied force or operator technique, the proposed approach considers process controllability as a systemic property determined by the reproducibility of the impact cycle, stability of adhesive contact, friction conditions, and tool kinematics. A comparative analysis of cold and hot glue applications is carried out with consideration of contact formation conditions, thermal and time-related factors, friction stability, and their influence on stress redistribution during localized deformation of aluminum panels. The scientific novelty of the study lies in the development of an original applied model of the PDR process with a magnetic return mechanism, within which the adhesive layer is interpreted as a medium of impulse transmission, while the magnetic return mechanism is considered as a stabilizing element ensuring reproducible cyclic loading and reducing variability of local stress states. The obtained results show that controllability of localized aluminum deformation emerges from the interaction between contact parameters, impact-cycle kinematics, and the mechanical limits of aluminum plasticity. The proposed approach expands the theoretical understanding of PDR processes under conditions of limited deformation stability and may be of interest to researchers in sheet metal forming and repair technologies, as well as to practitioners engaged in paintless dent removal.

Keywords: *Paintless Dent Repair, Aluminum Body Panels, Cold Glue, Adhesion, Friction, Contact Mechanics, Impact–Traction Loading.*

INTRODUCTION

In recent years, the automotive industry has been actively transitioning to the use of lightweight structural materials, driven by the need to reduce vehicle weight, improve fuel efficiency, and lower CO₂ emissions. One of the key directions has been the widespread adoption of aluminum alloys in body structures [2]. Due to their low density and high strength-to-weight ratio, aluminum panels are increasingly used in exterior automotive components, particularly in modern and premium vehicles [13]. However, the growing share of aluminum is accompanied by increased complexity

in repair processes, as its behavior under localized deformation differs significantly from that of conventional steels. At the same time, the structure of the automotive repair market is evolving. A substantial portion of claims in the insurance segment is associated with local damage without coating failure, primarily caused by hail and parking impacts [5]. Under these conditions, Paintless Dent Repair (PDR) technology is becoming increasingly widespread as a minimally invasive method for restoring the geometry of body panels without repainting.

Despite its advantages, the application of PDR to aluminum

Citation: Oleksandr Davydenko, “Application of a Slide Hammer with a Magnetic Return Mechanism in Cold Glue PDR Technology: A Comparative Analysis and Features of Working with Aluminum Body Panels”, Universal Library of Engineering Technology, 2026; 3(2): 93-100. DOI: <https://doi.org/10.70315/uloap.ulete.2026.0302015>.

is associated with several limitations. The material exhibits a lower ability to recover its shape, a narrow range of stable deformation, and high sensitivity to overstretching, which requires a different working approach based on the gradual redistribution of force. Additional challenges arise from the use of adhesive systems: hot glue requires time for heating and often demonstrates unstable adhesion due to the high thermal conductivity of aluminum, whereas cold glue provides more stable contact but requires precise control of the applied force [17]. The design of the tool also plays a significant role. Variability in the impact cycle of a conventional slide hammer reduces process controllability and increases the risk of defects. Under these conditions, the primary task becomes ensuring the stability and reproducibility of impact–traction loading when working with aluminum panels.

In practical PDR operations on aluminum body panels, these limitations become especially noticeable during repeated glue-pull correction of extended dents. Even under visually similar damage conditions, aluminum panels may respond differently to sequential pulling cycles due to variations in adhesive contact stability, impulse repeatability, and local stress redistribution. In routine repair practice, this often leads to overstretching, unstable deformation behavior, loss of pulling precision, or difficulties during final correction stages. These practical observations formed the basis for further analytical interpretation of the relationship between adhesive interaction, impact-cycle stability, and controllability of localized deformation.

The aim of this study is to develop and analytically substantiate an original applied model for the use of a slide hammer with a magnetic return mechanism in cold glue PDR technology when working with aluminum body panels. To achieve this aim, the following objectives are defined:

- to investigate the mechanisms of impulse transmission through the adhesive interface during the application of cold and hot glue;
- to determine the influence of contact interaction parameters on the stability of localized deformation of aluminum panels;
- to develop a contact-mechanical model of cyclic impact–traction loading;
- to assess the influence of slide hammer kinematic stabilization on the controllability of the PDR process.

The research hypothesis is that stabilization of impact–traction kinematics through the use of a magnetic return mechanism makes it possible to improve the controllability of localized deformation in aluminum panels, ensure more uniform force transmission, and reduce the risk of defects during PDR.

Scientific Novelty and Author’s Applied Model

The scientific novelty of the study lies in shifting the analysis of PDR technology from a descriptive level to a contact-

mechanical interpretation of the pulling process. In this interpretation, process stability depends on reproducibility of the impulse and on the way it is transmitted through the adhesive interface under conditions of nonlinear aluminum behavior. Unlike traditional approaches focused mainly on the tool and operator technique, this study examines the interaction between adhesive contact stability, friction conditions, the narrow plastic deformation window of aluminum panels, and variability of the impact cycle.

The author’s applied model proposed in this study considers the PDR process as a closed cyclic system of localized impulse–traction loading transmitted through an adhesive interface. The model integrates four interconnected elements: adhesive contact stability, friction conditions at the interface, reproducibility of slide hammer kinematics, and the limited plastic deformation window of aluminum panels. In the proposed model, the magnetic return mechanism contributes to stabilization of cyclic loading conditions, resulting in more repeatable impulse transmission and more controlled deformation behavior of aluminum panels.

MATERIALS AND METHODS

The study is based on methods of theoretical analysis of scientific publications, comparative interpretation of approaches to PDR technology, and categorization of factors determining the efficiency of localized pulling of aluminum body panels. The primary focus is placed on identifying the mechanisms of force transmission through the adhesive interface, the influence of friction and adhesion on contact stability, and the role of impact–traction kinematics under conditions of nonlinear deformation behavior of aluminum. The PDR process is considered as a systemic interaction between the tool, adhesive layer, and material, in which the outcome is determined by the consistency of contact, mechanical, and thermomechanical factors rather than solely by the magnitude of the applied force.

The study is conducted in the format of a systematic review of open-access scientific publications for the period 2022–2025, presented in international peer-reviewed journals and academic databases. The literature search was carried out using Google Scholar, ScienceDirect, SpringerLink, and MDPI with combinations of the following keywords: “paintless dent repair,” “cold glue,” “adhesion,” “aluminum deformation,” “sheet metal forming,” “contact mechanics,” “friction,” and “incremental forming,” applying AND/OR operators. The selection included English-language publications containing experimental results or analytical reviews related to localized aluminum deformation, adhesion interactions, and forming processes. Studies limited to narrow technological aspects without applicability in a broader analytical context, as well as those unrelated to localized shape restoration, were excluded.

At the initial screening stage, 38 publications were identified. After removing duplicates and evaluating titles and abstracts, sources that did not meet the research

objectives were excluded. As a result of full-text analysis, 15 studies were included in the final sample, reflecting key aspects of deformation mechanics, adhesion, friction, and thermomechanical effects in aluminum materials.

The analytical procedure included sequential stages of source selection, thematic filtering, full-text analysis, and systematization of results. The analysis identified the following groups of factors: characteristics of the adhesive interface and friction conditions, limits of stable deformation of aluminum, local thermomechanical effects, and variability of the tool's impact cycle. It was established that adhesion and friction determine the nature of force transmission and contact stability, while aluminum demonstrates high sensitivity to deformation redistribution. It was also shown that temperature effects may occur even in the absence of external heating and influence material plasticity, whereas instability of the impact cycle leads to an increase in defects.

The limitations of the study are associated with the relatively small sample size and the predominance of analytical and review-based publications. A significant portion of the studies addresses individual aspects of deformation or material joining, while a systemic interpretation of processes analogous to PDR remains limited.

The obtained results are used to systematize the factors influencing the efficiency of PDR when working with aluminum body panels and to develop an original model reflecting the relationship between adhesion characteristics, deformation parameters, and the stability of impact-traction loading.

RESULTS AND DISCUSSION

Within the conducted analysis of cold glue PDR, it is established that the process of localized pulling of an aluminum panel is primarily governed by the way the force is transmitted through the adhesive interface and by the stability of repeated impulse loading [6]. To formalize

the process, a system of parameters is introduced: h as the effective thickness of the adhesive layer, μ as the coefficient of friction at the interface, ΔF as the variability of the impact impulse, and σ_{loc} as the local stress state of the panel. Their interaction defines the deformation regime, which may result in controlled lifting, redistribution, or local overstretching [8]. In this framework, PDR is considered a process of impulse transmission through an intermediate layer rather than a series of independent mechanical actions.

Recent studies of glue-pull repair indicate that cold glue creates adhesion over a larger contact area and allows metal movement to occur more uniformly rather than concentrating force at a single point [10]. This improves the stability of deformation and reduces the risk of local overstretching. In contrast, hot glue provides higher peak adhesion but introduces time-dependent variability due to curing and temperature effects.

Analysis of the reviewed studies suggests that cold glue forms an intermediate layer with variable thickness h , which determines the configuration of the shear zone between the adapter and the metal. As h decreases, the shear zone becomes localized, the contact stiffens, and the load is transmitted with minimal losses. As h increases, the shear zone expands, internal deformation of the adhesive intensifies, and part of the energy is dissipated. This alters the ratio of normal and tangential components of the load and affects the pattern of local material flow in aluminum. To explain how adhesive contact stability influences force transmission during PDR operations, it is necessary to consider the parameters governing shear interaction inside the adhesive layer. Although the summarized parameters originate from studies of adhesive interaction and sheet deformation, they make it possible to systematize the factors affecting impulse transmission, friction stability, and controllability of localized pulling in aluminum PDR applications. Table 1 presents the parameters defining the conditions of contact interaction and the regime of force transmission.

Table 1. Key technological parameters and conditions of contact interaction (Compiled by the author based on Source: [1])

Parameter	Value	Object / Condition	Analytical significance
Steel sheet thickness	1,2 mm	High-strength steel	Forms a rigid support for contact
A5052-H34 sheet thickness	1,5 mm	Aluminum alloy	Determines the local deformation zone
Adhesive application amount	150 g/m ²	Baseline conditions	Defines the adhesive layer thickness h
Punch velocity	26 mm/s	Loading	Affects the dynamics of force transmission
Holding force	5 kN	Contact	Limits adhesive outflow
Particle diameter	15 / 97 / 244 μ m	Filler	Controls the coefficient of friction μ

Based on these parameters, a stable relationship is identified. An increase in the adhesive layer thickness leads to greater internal shear, which reduces the efficiency of impulse transmission and shifts the process from a lifting regime toward surface stretching. An increase in the coefficient of friction, achieved through fillers or surface roughness, limits sliding and returns the system to a controlled lifting regime.

In a number of studies, adhesive joints are evaluated in terms of strength and stiffness [1, 4]. This approach does not account for the specifics of PDR. Shape recovery is strongly associated with stable impulse transmission during cyclic loading rather than with peak adhesion force alone. Adhesive pull-off dynamics studies show that tensile force in viscoelastic adhesive interfaces increases with pull-off

velocity, and impulse loading may shift the failure mode from interfacial crack propagation to quasi-uniform detachment. This supports the interpretation of PDR as impulse-driven adhesive deformation. Under unstable contact conditions, micro-deformations accumulate, manifesting as residual surface waviness [14].

The reviewed studies and practical observations indicate that the parameter ΔF becomes critical under repeated loading conditions. As impulse variability increases, the deformation zone shifts from the center of the dent toward the periphery. This leads to non-uniform stress distribution and the formation of local stress concentrations. Reducing variability stabilizes the contact and keeps the deformation within a controlled regime [18]. In practical aluminum PDR operations, instability of repeated impulses is especially noticeable during sequential correction of extended dents, where even minor variations in return kinematics may alter stress redistribution across the panel surface and complicate final finishing stages.

Contact interaction is determined not only by macroscopic parameters. The microrelief of the aluminum surface also

influences the process. Under localized loading, redistribution of peaks and valleys occurs, forming a new surface profile. Even with correct panel geometry, local inhomogeneities may persist due to uneven force transmission [12].

The analysis shows that aluminum panels are characterized by a narrow range of allowable localized deformation. This range is determined by the combination of material strength, thickness, and temperature state. Unlike steel, aluminum does not exhibit pronounced elastic recovery. Deformation requires sequential redistribution of stresses rather than a single loading event. Since aluminum PDR is performed within a relatively narrow deformation window, the mechanical limits of sheet materials become directly related to the risk of local overstretching during glue pulling. Although these parameters originate from material forming and deformation studies rather than direct PDR experiments, they provide a basis for understanding the deformation limits within which localized aluminum repair is performed. Table 2 presents quantitative benchmarks reflecting the range of deformation-related parameters relevant to aluminum panel behavior during localized pulling.

Table 2. Quantitative benchmarks for deformation of aluminum sheets (Compiled by the author based on Source: [4])

Quantitative parameter	Value 1	Value 2	Value 3
Sheet blank thickness, mm	0,1	1,2	12,0
Material tensile strength, MPa	700	800	980
Thermal treatment parameters (AA7075-T6)	250 °C	3 s	7075
Steel tailor welded blanks thickness, mm	1,2	1,4	14
Aluminum tailor welded blanks thickness, mm	2.0	2.5	5052
Sheet thickness in solid-state processes, mm	2.0	4.0	6.0

Note: Column "Value 1" represents baseline or lower-bound conditions of the parameter, "Value 2" reflects intermediate or commonly used operating conditions, and "Value 3" corresponds to upper-bound values, extended ranges, or material/design-specific identifiers (e.g., alloy designation in the case of AA7075-T6 or material grade references for tailor-welded blanks).

Based on the comparison of parameters, the following relationship is established. An increase in thickness and strength leads to a higher required force. This narrows the range of allowable deformation and increases the likelihood of local overstretching [3, 13]. Increasing tool power without controlling impulse transmission does not improve the result.

The behavior of aluminum is nonlinear. At the initial stage, a rapid shape recovery is observed. This is followed by a stabilization stage, where additional loading results in stress redistribution rather than an increase in deformation amplitude. When the critical level of σ_{loc} is exceeded, local instability occurs, manifested as a sharp point or microstructural damage [9]. Temperature effects further intensify these phenomena. The influence of temperature on the deformation behavior of aluminum under localized loading is illustrated in Figure 1.

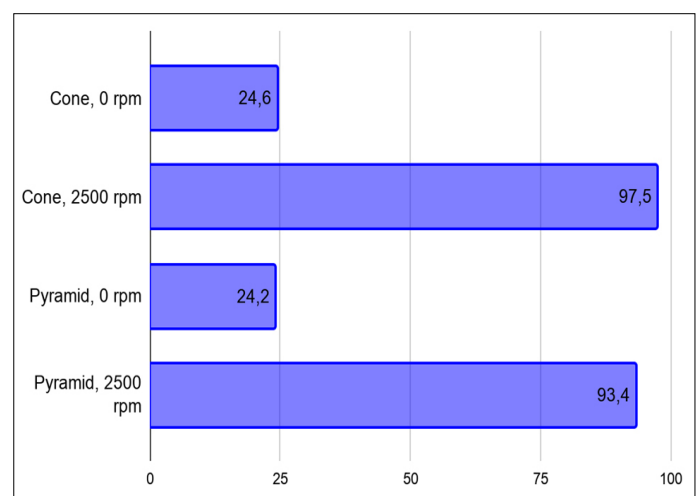


Figure 1. Maximum temperature during localized deformation of aluminum (compiled by the author based on Source [15])

Even moderate temperature variations affect the plasticity of the material and alter the stress distribution [7]. Unlike laser forming processes, where temperature acts as the primary deformation factor [11], in PDR, it plays a secondary role. However, its influence on process stability remains significant.

In a number of studies, the expansion of the technological window is achieved by adjusting temperature or geometric parameters [3, 10]. Under PDR conditions, this approach is limited. The key requirement is maintaining deformation within the allowable range through stable impulse transmission and controlled contact interaction.

Instability of aluminum deformation arises from the combined influence of parameters h , μ , and ΔF . Under unfavorable combinations, the process transitions from controlled lifting to local overstretching. Reducing impulse variability and controlling friction make it possible to keep the process within a regime of uniform deformation redistribution and to minimize the risk of defects.

Based on the reviewed studies and practical interpretation of aluminum PDR operations, the PDR process may be considered as a coordinated system of force transmission through an adhesive interface under conditions of limited plasticity of aluminum. The analysis focuses on the structure of impulse loading and the conditions of its reproducibility. The combination of adhesion, friction, and kinematics determines process stability and defines the boundaries of allowable deformation.

The comparison of hot and cold glue reveals differences at the level of contact formation and its behavior under load. Hot glue provides adhesion through a phase transition, introducing a time interval between application and the onset of force transmission. During this period, the contact zone remains unstable, and stresses are distributed unevenly. For aluminum, this effect is amplified by high thermal conductivity, which accelerates cooling and reduces adhesion in localized areas [20]. Cold glue forms contact without a transitional stage. Force transmission begins immediately after adapter fixation, eliminating the time gap and stabilizing the adhesion zone. Shear stresses are distributed more evenly, which affects the deformation pattern and reduces the likelihood of local overstretching.

Differences are also observed in friction behavior. When using hot glue, the coefficient of friction changes during cooling, leading to contact instability. In cold glue, friction is established immediately and remains nearly constant throughout the cycle. This stability ensures predictable interaction between the adapter and the panel surface. Studies of adhesive joints confirm that friction stability determines material flow behavior and deformation shape [16].

The process rate is determined by cycle continuity. Hot glue

requires pauses, disrupting the loading rhythm and altering contact conditions between impacts. Cold glue enables a continuous cycle in which each impulse is superimposed on an already formed stress state. This mode is particularly important when processing extended dents, where sequential redistribution of deformation is required.

Working with aluminum amplifies these differences. The low stability of plastic deformation requires uniform force transmission. Hot glue creates zones of detachment and repeated contact, leading to stress concentration. Cold glue forms a stable contact zone in which the load is distributed over the surface. Studies on aluminum alloy forming show that uniform force transmission determines the stability of the deformation process.

Thus, the difference between adhesives is manifested through contact mechanics. Hot glue creates variable interaction conditions, whereas cold glue ensures a steady-state mode of force transmission. This regime becomes the basis for process control through tool kinematics.

Aluminum panels are characterized by a limited range of stable plastic deformation. Modern research shows that the operational window of paintless dent repair is defined by metallurgical constraints and material plasticity limits. Aluminum panels exhibit a narrow deformation range, requiring controlled loading and gradual redistribution of stresses during repair. After unloading, pronounced shape recovery is absent. Any operation is retained in the material structure and affects subsequent behavior.

Increased stiffness requires a significant force to initiate deformation. After transitioning into the plastic state, a tendency toward localization is observed. A narrow zone forms in which stresses are concentrated. Under uneven force transmission, this zone shifts, leading to secondary defects. The risk of overstretching is determined by the proximity of the strength limit to the plasticity range. For aluminum alloys, tensile strength reaches 700–980 MPa with limited plasticity [3]. Even a slight excess of the allowable stress level results in defect fixation.

Temperature influences the nature of deformation. Heating to the range of 50–70°C reduces deformation resistance and increases plasticity. The material begins to flow more uniformly, which reduces the likelihood of localization. Studies on thermomechanical behavior confirm the influence of temperature on deformation distribution [19].

Gradual pulling is a necessary condition for operation. Abrupt loading creates local stress peaks. Sequential application of force ensures redistribution of deformation over the area and maintains the process within the allowable range. This approach is directly related to the mechanical properties of the material. The analysis shows that the reproducibility of the impulse emerges as the critical parameter governing deformation stability. The process is considered as a closed

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cycle in which each stage affects the subsequent one. Figure 2 presents the author's model of the cyclic PDR process, reflecting the sequence of formation and transmission of impulse loading within the system. A slide hammer operates by transferring inertial impact force from a moving mass

along a shaft to the attached object. When the sliding weight strikes the stop, the momentum is converted into a pulling impulse acting on the dented panel. The magnitude of this impulse depends on mass, velocity and stroke length, which determine the repeatability of deformation loading.

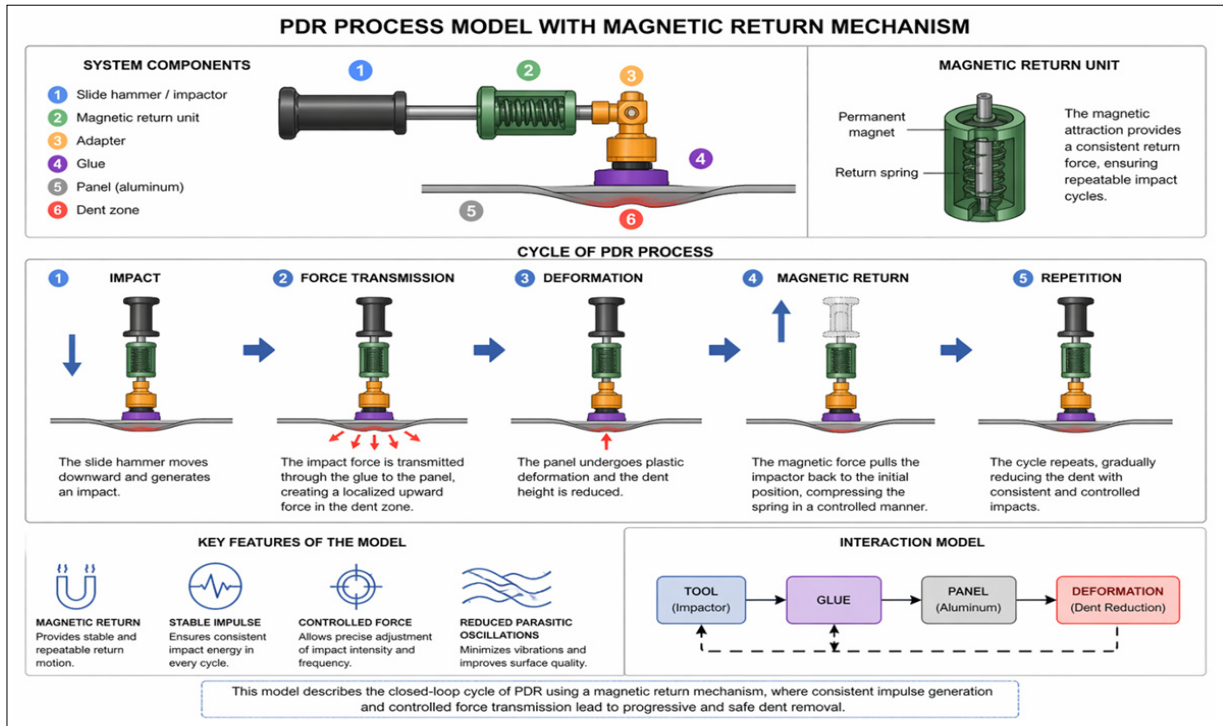


Figure 2. PDR process model with a magnetic return mechanism (author's development)

The model identifies a sequence of stages: impact, force transmission, deformation, return, and repetition. A loss of stability at any stage alters the behavior of the entire system. In conventional tools, variability in the return phase leads to fluctuations in impulse parameters, resulting in non-uniform stress distribution.

The magnetic return mechanism establishes fixed kinematics of motion. The return of the striking element occurs with a defined speed and amplitude, which limits variability in cycle parameters. As a result, a series of impulses with similar characteristics is generated, reducing overall variability.

According to the author's practical observations obtained during routine PDR operations on aluminum body panels, the use of a slide hammer with a magnetic return mechanism provides a stable operating cycle reaching approximately 20 impact actions per minute. Compared with conventional slide hammer systems, the stabilized return phase contributes to an increase in repair speed of approximately 50% under typical repair conditions. The slider mechanism also enables one-handed operation, improving controllability during sequential localized pulling and reducing unnecessary operator movements. In practical applications, stabilization of impulse transmission additionally reduces the likelihood of excessive local loading, contributing to the preservation of paint coating integrity and allowing the vehicle to be returned to service more quickly after repair.

Impulse stabilization directly affects the behavior of aluminum. Under unstable loading, individual impulses may exceed the allowable range, causing local overstretching. Under a controlled cycle, stresses are maintained within the plastic deformation window. Process control is thus achieved through the structure of loading rather than by increasing force.

Controllability is manifested in the predictability of load transmission. The need to compensate for instability through excessive force is eliminated. The likelihood of shifting the force application zone is reduced. Parasitic oscillations caused by irregular return are largely eliminated.

Existing approaches usually interpret adhesive as a fixation medium and the tool as the primary source of pulling force. The present analysis interprets the adhesive layer as an impulse-transmission interface, while the magnetic return mechanism contributes to stabilization of the loading cycle. This combination forms a controlled regime of cyclic loading and makes it possible to maintain deformation within the mechanical limits of aluminum panels.

CONCLUSION

The conducted analysis demonstrates that stable deformation control during aluminum PDR operations depends on coordinated interaction between adhesive contact conditions, impulse reproducibility, friction stability,

and impact-cycle kinematics. The reviewed studies and practical interpretation of aluminum glue-pull repair processes indicate that instability of repeated loading cycles plays a critical role in the formation of local overstretching, uneven stress redistribution, and loss of pulling precision during sequential correction of aluminum panels.

The proposed contact-mechanical interpretation expands the understanding of PDR beyond conventional operator-dependent repair approaches and allows the process to be considered as a reproducible system of cyclic impulse transmission through an adhesive interface. Within this framework, the magnetic return mechanism contributes to stabilization of loading conditions, improves repeatability of impulse transfer, and supports more predictable deformation behavior under conditions of limited aluminum plasticity.

The analysis also demonstrates that cold glue technology creates more stable contact interaction conditions during repeated localized pulling due to continuity of the loading cycle and reduced variability of friction behavior. Under aluminum repair conditions, these factors become directly related to deformation controllability and the reduction of local defect formation.

Practical observations obtained during routine PDR operations additionally indicate that stabilization of return kinematics contributes to improved repair consistency, reduction of unnecessary corrective actions, and higher operational efficiency during sequential aluminum panel correction.

The proposed model creates a basis for transition from empirically controlled PDR operations toward mechanically interpretable and reproducible deformation control of aluminum panels. Further development of this approach may contribute to quantitative optimization of glue-pull repair systems and to the design of repair tools adapted to the narrow plastic deformation window of aluminum body structures.

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