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ТЕПЛОЕНЕРГЕТИЧНЕ ВИДАЛЕННЯ ЗАДИРОК З ВИКОРИСТАННЯМ ЗЕЛЕНОГО ВОДНЮ

Анотація: У статті досліджується процес термічного видалення задирок за допомогою зеленого водню, з акцентом на потребу авіакосмічної промисловості у легких, міцних полімерних матеріалах з високою якістю поверхні. Метод передбачає контрольований вибух суміші водню та кисню для усунення задирок на пластикових компонентах, поєднуючи тепловий і тисковий впливи для обробки поверхні. У дослідженні моделюються складні взаємодії під час процесу видалення задирок із використанням програмного забезпечення LS-DYNA та методу I-SPG. Робота демонструє ефективне видалення задирок і згладжування поверхні, але також підкреслює необхідність уточнення початкових параметрів і проведення повномасштабних експериментів для підвищення точності та надійності чисельного моделювання.

Ключові слова: Термічне видалення задирок, зелений водень, обробка поверхні, плавлення пластику, LS-DYNA.

THERMAL ENERGY DEBURRING WITH GREEN HYDROGEN COMBUSTION

Abstract: This article investigates the process of thermal energy deburring using green hydrogen combustion, with a focus on the aerospace industry’s need for lightweight, durable plastic materials with high surface quality. The method involves a controlled explosion of a hydrogen-oxygen mixture to remove burrs from plastic components, combining heat and pressure effects for surface finishing. Utilizing LS-DYNA software and the I-SPG method, the study models the complex interactions during the deburring process. The research demonstrates effective burr removal and surface smoothing, but also emphasizes the need for further refinement of initial parameters and full-scale experimental validation to improve the accuracy and reliability of the numerical simulations.

Keywords: Thermal deburring, green hydrogen, surface finishing, plastic melting, LS-DYNA.

In the modern aerospace industry, polymers and plastic materials play a crucial role due to their lightweight, strength, and resistance to aggressive environments. The incorporation of these materials not only reduces the weight of aircraft but also enhances their operational performance. A key aspect of the manufacturing process is the surface treatment of plastic components, which improves their physico-mechanical properties and durability. High-quality surface treatment, including mechanical, thermal, and chemical methods, helps eliminate defects, improve adhesion, and ensure the reliability of components critical for the safety and efficiency of aerospace technology. The integration of innovative technologies such as 3D printing and laser processing opens up new possibilities for advancing and raising the quality standards within the industry.

This report presents the process of deburring using green hydrogen combustion from a solid mechanics perspective. This is an innovative technique that leverages a controlled explosion of hydrogen-oxygen mixtures to remove burrs from manufactured parts in a sustainable, efficient way.

In the process of thermal deburring in a specialized chamber, rapid combustion of hydrogen occurs, creating an environment with high temperature and pressure. This sequence of events begins with the ignition of a carefully balanced mixture of hydrogen and oxygen (or dried air), which initiates a highly exothermic combustion reaction. The combustion process releases significant heat energy, rapidly increasing the temperature within the chamber. The production of water vapor as a byproduct of hydrogen combustion further drives a sharp rise in pressure as the gases expand.

The rapid release of energy creates a pressure wave that propagates through the chamber and impacts the workpiece, targeting burrs on its surface. These burrs, due to their small size and thin structure, absorb heat much more quickly than the bulk material, reaching high temperatures almost instantly. This leads to their softening and eventual melting, with some burrs undergoing vaporization or oxidation depending on the process conditions. Simultaneously, the pressure wave exerts a mechanical force on the burrs, aiding in their removal or reintegration into the workpiece's surface. The gases produced, primarily water vapor in the case of hydrogen combustion, are then expelled from the chamber as the system cools, preparing for the next cycle.

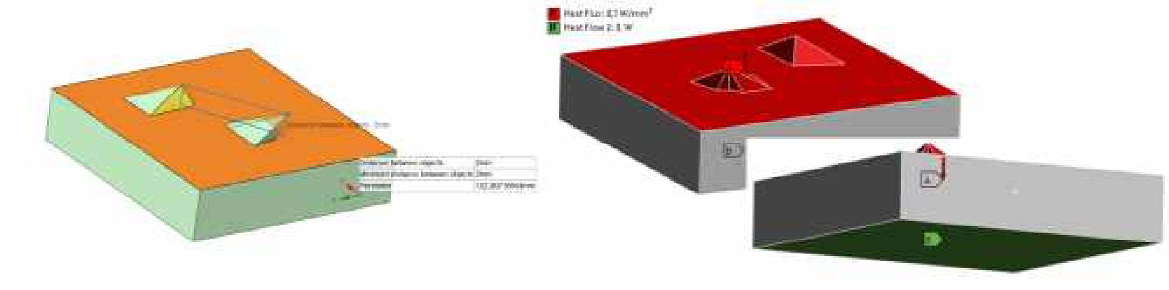
This method is believed to efficiently remove surface imperfections without damaging the underlying material, relying on thermodynamic principles of rapid gas expansion, heat transfer, and mechanical displacement to achieve precise results. Our work is aimed at selecting such parameters of this process, in which burrs are either removed or smoothed on the surface of the part, which improves the overall quality of the workpiece.

When processing the surface of a part with a thermal wave, it is obvious that at a minimum the surface of the part will heat up and the burrs will be fully or partially heated, which will lead to uneven thermal expansion of the sample. While this expansion tends to be uniform in the bulk of the material, smaller features such as burrs are more affected due to their size and geometry. Burrs, being thin and sharp, are particularly susceptible to heat because their small mass allows them to absorb heat more rapidly than the surrounding bulk material.

The rate of heat absorption is largely determined by the thermal conductivity of the material, and in metals, this leads to localized softening or even melting of the burrs. Because the burrs have a lower heat capacity compared to the larger mass of the workpiece, they reach critical temperatures more quickly, causing them to lose their mechanical strength. This localized weakening allows for easier removal or reintegration of the burrs into the surface without compromising the structural integrity of the main body of the material.

In essence, heat reduces the yield strength of the burrs by promoting thermal expansion and softening, making it easier to remove them. This process, combined with the potential for oxidation at high temperatures, facilitates burr elimination while minimizing damage to the rest of the material.

An illustrative example of the thermal effects on burrs (fig. 1) can be observed through a numerical model designed for thermal analysis using ANSYS environment [1]. In this model, the geometry of the polyethelene sample consists of two pyramidal structures representing hypothetical burrs or surface roughness. The initial height of the burrs is set at 2 mm, providing a baseline for comparison.



a) b)

Fig. 1. Heat problem statement: a) sample geometry: b) boundary conditions

During the thermal processing of a thermoplastic part, the surface layer, including the burrs, enters a molten state, while the bulk of the material remains solid (fig. 2). The depth of burr melting has been found to vary between 0.5 mm and 1.6 mm, highlighting the localized effect of heat on the burrs compared to the rest of the part.

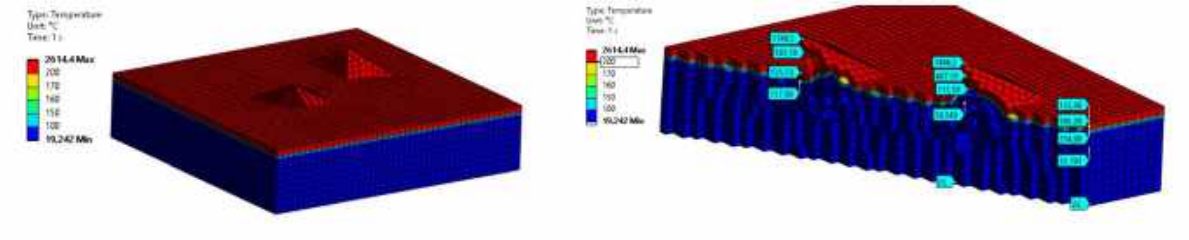


Fig. 2. Temperature field in the sample with burrs

The pressure wave generated by the combustion process exerts a substantial mechanical effect on the material, particularly in areas of surface roughness. The rapid, high-pressure loading from the pressure wave causes the burrs to undergo plastic deformation. As natural experiments have shown, due to their softened state from the preceding heat, the burrs thicken and integrate into the main part rather than breaking or shearing off. This leads to the redistribution and fusion of burr material into the surface, effectively smoothing it. Additionally, the high strain rates induced by the pressure wave enhance material flow, particularly in the molten or softened regions of the burrs. Under such conditions, plastics tend to exhibit more ductile, fluid behavior, allowing for the absorption of burr material into the main body rather than detachment. This behavior results in a thickened, smoothed surface layer where the material is evenly redistributed, significantly improving the surface integrity of the part.

During the thermal deburring process, the workpiece may temporarily exist in two distinct phase states: the surface layer, including the burrs, becomes molten, while the core remains solid. This distinction is crucial for ensuring that only the surface material and burrs are affected, preserving the structural integrity of the core. To accurately model this two-phase state, advanced simulation tools are necessary, particularly for capturing the dynamic interactions between fluid and solid phases. In this context, the LS-DYNA [2] dynamic solver is employed, which effectively models fluid-solid interactions within a Lagrangian formulation and is able to capture the complex interactions that occur when the workpiece transitions between solid and molten states during processing.

The combined effects of heat and pressure wave during hydrogen-based thermal deburring are central to this analysis. The initial condition assumes that the part is first heated, followed by the application of pressure resulting from the detonation of a hydrogen-oxygen mixture. However, alternative scenarios where the pressure is applied before the part is sufficiently heated warrant further investigation. In such cases, the material would retain a higher degree of rigidity, as it has not yet undergone sufficient thermal softening. For instance, in an unheated state, a pressure of 3 atmospheres may not be adequate to induce substantial deformation, particularly in materials with higher stiffness. Here, the material remains predominantly solid, limiting the mechanical effects to the static excess pressure within the chamber.

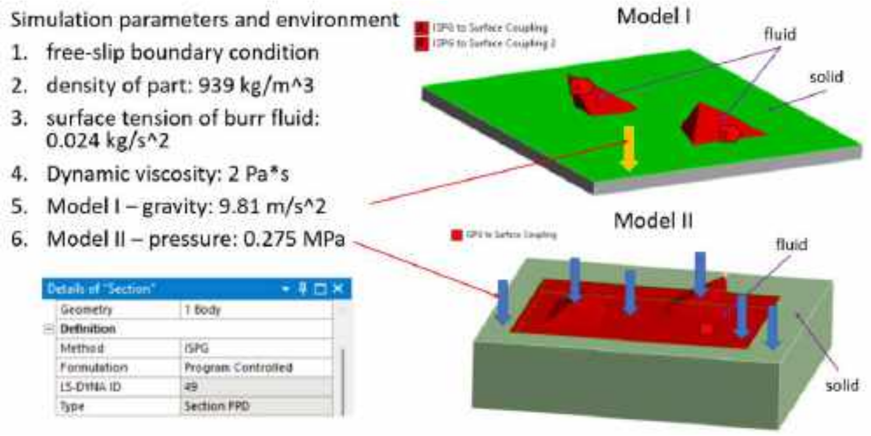
For a brief period, the material may exist in two distinct phase states: a heated, softened surface layer and a cooler, more rigid core. The challenge lies in accurately simulating and understanding this dual-phase behavior. To do so, we propose using the Incompressible Smoothed Particle Galerkin method (I-SPG) within the Lagrangian framework. This approach is particularly suited for modeling multi-phase interactions and provides the ability to account for both the thermal and mechanical effects on the material without altering the underlying formulation.

The I-SPG method offers a balance between computational efficiency and accuracy. By incorporating both heat and pressure effects into a single model, we can minimize labor costs and maximize productivity. This method allows us to simulate the complex interaction of the pressure wave and the part’s surface in a realistic, industrial context, while maintaining the simplicity of the traditional Lagrangian formulation. This method, which combines Smoothed Particle Hydrodynamics and Galerkin finite element techniques, is particularly useful in handling large deformations and multi-phase material interactions. It is also mesh-free, avoiding the complications that arise with traditional mesh-based methods in scenarios with high deformation. I-SPG was developed in [3–6].

The primary advantages of this method include its ability to accurately model both thermal expansion and pressure effects during the deburring process. Additionally, it provides enhanced simulation fidelity, particularly in capturing phase transitions from solid to molten states, which are critical during thermal processing. Furthermore, the method ensures mass conservation and fluid dynamics are accurately represented, without the limitations imposed by traditional mesh-based approaches.

As numerical experiments have shown, I-SPG is more suitable than another widely used calculation method, ALE (Arbitrary Lagrangian-Eulerian) due to its robustness in handling large deformations, phase transitions, and its ability to model dynamic interfaces more efficiently in a Lagrangian context, making it ideal for hydrogen-based deburring processes.

The next numerical experiment involves the consideration of two models shown in the fig. 3 within the LS-DYNA environment. These models simulate two-phase states, liquid and solid, using a Lagrangian formulation. In the solid phase, conventional thermo-mechanical properties are applied to represent the material's behavior, while the properties of the liquid phase are detailed separately, as shown in the accompanying data. In the first model, only the burrs are subjected to heating, while in the second model, the surface layer of the part itself is also heated.


Simulation parameters and environment

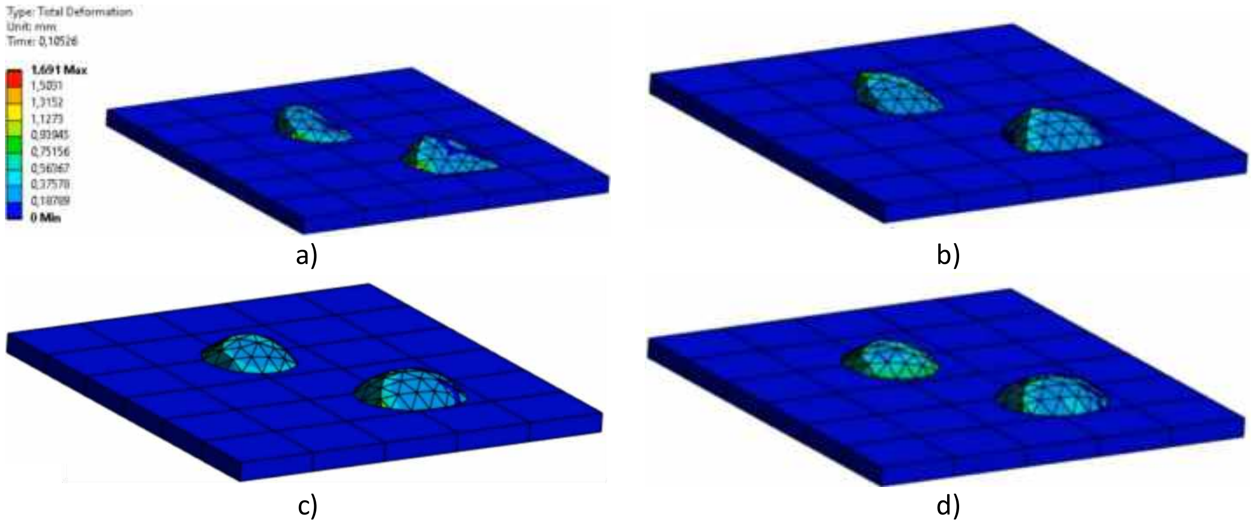
1. free-slip boundary condition
2. density of part: 939 kg/m^3
3. surface tension of burr fluid: 0.024 kg/s^2
4. Dynamic viscosity: 2 Pa*s
5. Model I – gravity: 9.81 m/s^2
6. Model II – pressure: 0.275 MPa

Details of "Section"

Geometry	1 Body
Definition	
Method	ISPG
Formulation	Program Controlled
LS-DYNA ID	49
Type	Section FPD

Fig. 3. Burr modelling in LS-DYNA

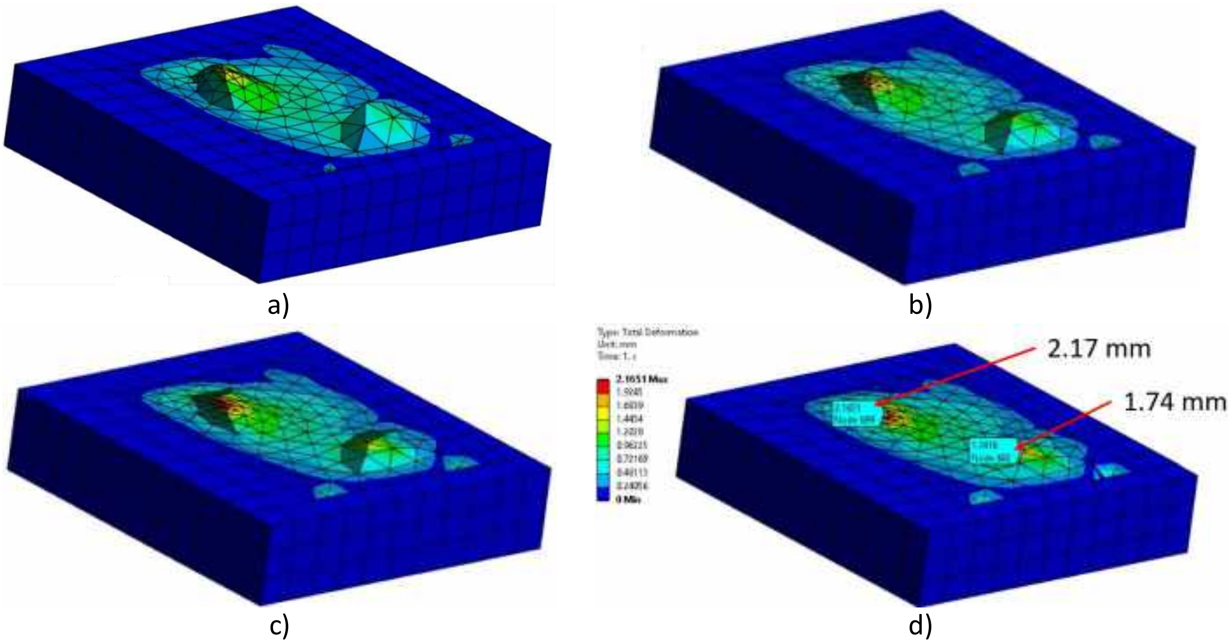
The results of surface finishing for two samples are presented. In the first case the effect of surface tension on the spreading of molten material across the part's surface is demonstrated in the fig. 4. In this case, only the effect of temperature is considered in addition to the surface tension. In the second case the combined effects of heat and pressure in addition to the surface tension are examined, resulting in deformation of both the part and its surface, as shown in the fig. 5. Both samples exhibit a significant reduction in surface roughness, with decreases of at least 1.7 mm observed.



a) b) c) d)

Fig. 4. Deformed state of model 1:
a) time 0.5 sec; b) time 1.0 sec; c) time 1.5 sec; d) time 2.0 sec

In conclusion, the simulation of the thermal energy deburring process utilizing green hydrogen combustion can be effectively achieved through the LS-DYNA software, which incorporates the I-SPG method. However, to enhance the accuracy and reliability of the results, it is essential to refine the initial parameters. This includes obtaining precise measurements of the actual surface roughness and defects present on thermoplastic components, as well as a comprehensive understanding of the material properties within the temperature range of 0 to 250 degrees Celsius, both prior to and following the melting point. Additionally, now we are conducting full-scale experiments that are necessary to validate the numerical model and ensure its applicability in practical scenarios.



a) b) c) d)

Fig. 5. Deformed state of model 2:
a) time 0.25 sec; b) time 0.5 sec; c) time 0.75 sec; d) time 1.0 sec

Acknowledgements

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