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Shape Deposition Manufacturing with Microcasting

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Abstract:

This paper provides a brief overview of an emerging application for solid freeform fabrication known as Shape Deposition Manufacturing (SDM) with Microcasting. The SDM microcasting process has been used to manufacture complex geometric shapes from CAD models. This novel manufacturing process is briefly described, and a sample artifact is shown. Our current research is described, involving the thermal behavior of the process, the bonding of deposited layers, and droplet fluid dynamics. We have gained significant understanding of the relationship between process parameters and the final quality of artifacts created by microcasting, and continue to investigate the effect of process parameters to develop a systematic representation of the parameter design space; current efforts are directed towards improving the numerical simulations to more accurately predict and control the microcasting process.

I. Introduction

The capability to automatically fabricate arbitrarily complex shaped three-dimensional parts, directly from CAD models, without part-specific tooling or human intervention is popularly referred to as solid freeform fabrication (SFF). An emerging application for SFF technologies is to create complex shaped metal structures such as custom tooling (e.g., injection mold dies). Current SFF systems, however, cannot directly fabricate fully dense steel structures. They can be used indirectly by quickly creating plastic or wax patterns, or ceramic shells for investment casting applications (Sachs et al., 1992), or for powdered metallurgy applications to create porous metal structures which must be subsequently infiltrated by low-melt alloys (Pintat et al., 1995; Sachs 1995) or hot isostatic pressed (Bampton 1995).

Shape Deposition Manufacturing (SDM) with a new weld-based process called microcasting (Prinz 1994a Patent; Weiss 1994a Patent; Weiss 1994b Patent; Weiss et al., 1992) is an SFF approach being developed to address the challenge of directly creating functional metal structures. The structures created are fully dense, with controlled microstructures and acceptable surface appearance, and are within specified dimensional tolerances. SDM also has unique capabilities to build multi-material structures with different materials in different regions of the part (Prinz 1994b Patent). One application is the manufacture of tooling with complex interiors such as an injection mold composed of an outer steel shell for strength, a copper interior for uniform heating/cooling, and cooling channels which conform to the shape of the surface of the tool.

The microcasting process deposits discrete droplets of super-heated metal. Concurrent efforts are underway to improve this process through a combination of experimental and

numerical techniques. Experiments investigate the influence of microcasting process parameters (e.g., plasma current, wirefeed rate, droplet standoff, etc.) as well as substrate roughness, to droplet characteristics and to the resulting deposited layer. A quantitative measure of artifact quality is the percentage volume of voids present in a deposited layer (Osio and Amon, 1996). Because of the large number of parameters, together with the combinations of materials involved in the microcasting process, we require an efficient method for selecting the parameter settings to perform the experiments. We have used a multistage approach to data collection, involving design of experiments and optimal sampling. This approach allows us to build surrogate models that embody all available knowledge about the influence of the different process control parameters on selected responses.

The goal of the numerical simulations is to understand the interface heat transfer at droplet impact, the spreading behavior of the solidifying droplet, and the overall cooling of both individual droplets and successive layers (Amon et al., 1994 and 1996a). Experiments also provide the process conditions such as the size, temperature and velocity of the droplet striking the substrate, while the numerical simulations yield the amount of partial substrate remelting, and cooling history. Residual stress build-up, inherent to SDM microcasting, can lead to reduced strength in parts, and induce undesirable effects such as part warping, loss of edge tolerance, and residual stress-driven inter-layer debonding (Beuth and Narayan, 1996). Mechanical numerical models must be coupled to thermal models because residual stress models depend on spatial-temporal temperatures obtained from the thermal models, and bond strength of successive layers is inherently linked to temperature-controlled substrate remelting. Predictive tools will aid in the selection of process parameters, help achieve the desired substrate remelting, and help control residual thermal stresses of the final artifact.

II. **SDM and** Microcasting

With SDM, parts are incrementally built-up using a combination of material deposition and material removal processes (Figure 1). Individual layer segments are deposited as near-net shapes and then accurately machined to net-shape before depositing additional material. Each layer consists of both primary material and sacrificial material. The sacrificial material is removed after the part has been completely built up. The sequence for depositing and shaping each layer segment depends upon depends on local geometry. Several deposition processes and material combinations are available. For one example, stainless steel and copper can be deposited with various welding processes. Copper serves as a sacrificial material and is removed with nitric acid.

The basic SDM strategy is to first slice the CAD model of the shape to be fabricated into layers while maintaining the corresponding outer surface 3D geometry information. The thickness of the layer varies depending on the part geometry. Each layer is further decomposed into layer segments, or "compacts", such that undercut features are not machined, but are instead formed by depositing onto previously machined segments. Each material in each segment is deposited as a near-net shape. After deposition, each compact is then precisely shaped to net shape using CNC milling. For the example shown in Figure 1, involving a complex shaped steel/copper part, the bottom layer is formed by: first depositing and shaping copper; then depositing steel into cavity formed by the copper; and finally planing the layer flat. In contrast, the upper layer is formed by the opposite sequence whereby the steel is deposited and shaped before copper is deposited. More

complex shaped layers, such as the second layer from the bottom, must be broken down into three or more compacts in order to form the multi-material layer

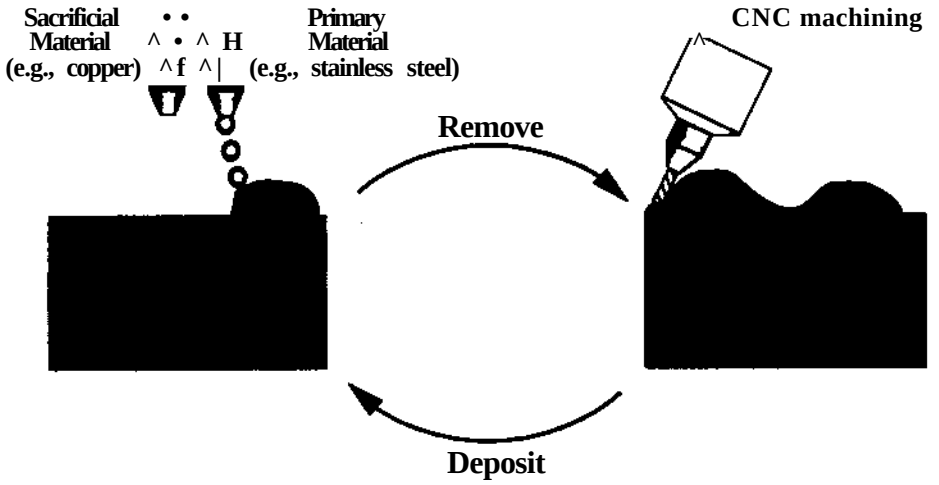


Figure 1. Shape Deposition Manufacturing

SDM can be implemented in several ways. In one approach, the parts are built-up on pallets which are transferred back-and-forth between a separate CNC milling stations and deposition stations using a robot (Merz, 1994). Another approach is to attach the deposition apparatus directly to the Z-axis housing of the CNC machine. As noted above, there are several alternative material combinations (including plastic, ceramics, and metals) and deposition processes being investigated for use in SDM. One process for metals is microcasting (Merz et al., 1994; Amon et al., 1996b), which is a hybrid weld-spray process producing discrete, super-heated metal droplets (Figure 2). An arc is established between a conventional plasma welding torch and feedstock wire which is fed from a charged contact tip. The wire melts in the arc, and when the droplet has accumulated enough molten material, its weight overcomes the surface tension by which it adheres to the wire. The droplet falls from the wire, accelerated by gravity, and flattens upon impact with the substrate. In contrast to the small droplets created with thermal spraying, the diameter of microcast droplets are on the order of millimeters. The plasma torch generates microcast droplets with a significant amount of superheat, and due to the large volume-to-surface ratio, the droplets remain superheated in flight and contain sufficient energy to locally remelt the underlying substrate at impact to form metallurgical bonding upon solidification. The substrate may be preheated to facilitate remelting and reduce stress buildup (Chin et al. 1997).

To control oxidation, it is critical to shield the droplets and substrate with inert gas. Placing the microcaster in an environmental chamber is feasible, but costly. A straight-forward alternative is to locally shroud the droplets and working area with a laminar curtain of shielding gas. For this purpose, we use a commercially available shrouding device from Praxair, Inc., Tarrytown, NY (US. Patent No. 4,823,680). A key advantage of the microcasting process stems from its low operational cost as well as the commercial availability of components such as the plasma welding torch, power supply, wire feed mechanisms, and inerting shrouds.

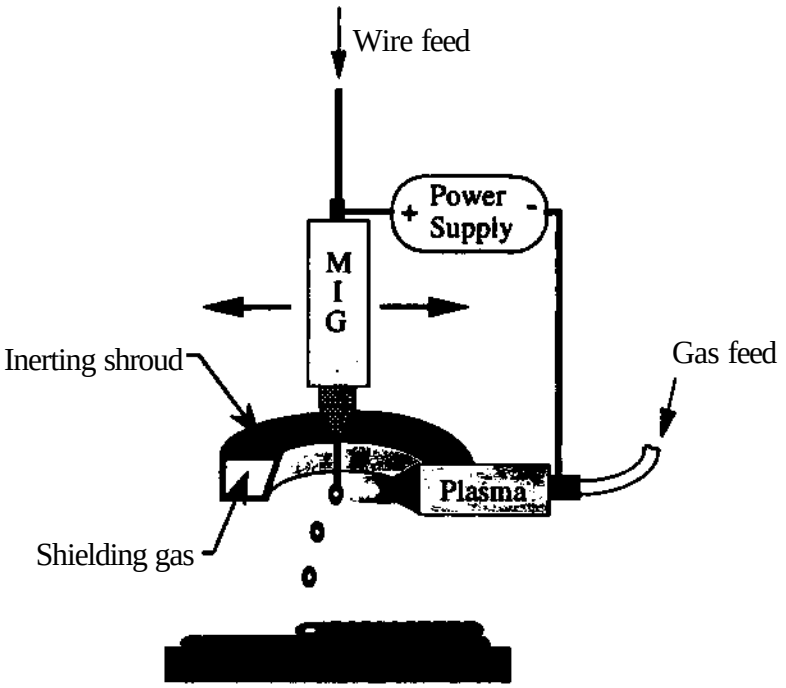
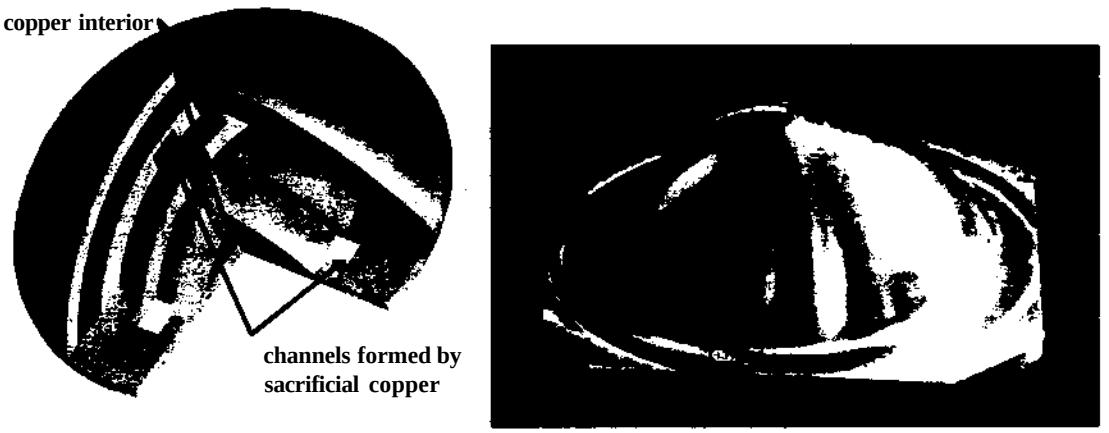


Figure 2. Microcasting apparatus

An example of a part manufactured using this approach, which could not be produced solely with machining is shown in Figure 3. This part is a hemispherical shaped structure with a 308 stainless-steel outer shell, a permanent copper interior, and conformable channels as depicted in the CAD drawing in Fig. 3b.



a. Completed steel/copper structure b. CAD rendering; cut-away view.

Figure 3. Multi-material, copper/stainless-steel structure built with SDM.

III. Description of Research

One principal focus of our microcasting research is to understand the rcmelting phenomenon, the thermal history of the process, the mechanical stresses generated, and the interaction of successive droplets to produce high quality (free of voids) layers. The ability to predict these events will allow us to select process parameters that optimize the quality of the final part, improve material properties through the control of melting conditions and cooling rates, protect sacrificial supporting structures having lower melting temperatures than the deposited material, and control thermal stresses.

To achieve these goals, we have performed experiments using calorimetry, thermocouple and optical metallographic techniques, as well as still and high-speed photography. In addition, analytical results based on the Stefan problem have been used to study the initial thermal interface conditions. The calorimetry and thermocouple experiments provide initial conditions for our models, as well as validation of the thermal model results (Schmaltz and Amon, 1996). Metallographic characterizations also allow cooling rates estimations, and the visualization of heat flow direction from the grain orientation. Figure 4 compares our initial one-dimensional modeling results for a carbon steel droplet striking an ambient carbon steel substrate with experiment results using thermocouples. The droplet histories are in good agreement initially, but the numerical results over-predict the temperature later in the cooling process. One-dimensional numerical results for the substrates do not agree as well, suggesting the need for multi-dimensional modeling. Initial thermal models involved only heat transfer, however current modeling is extended to the study of droplet deformation and solidification.

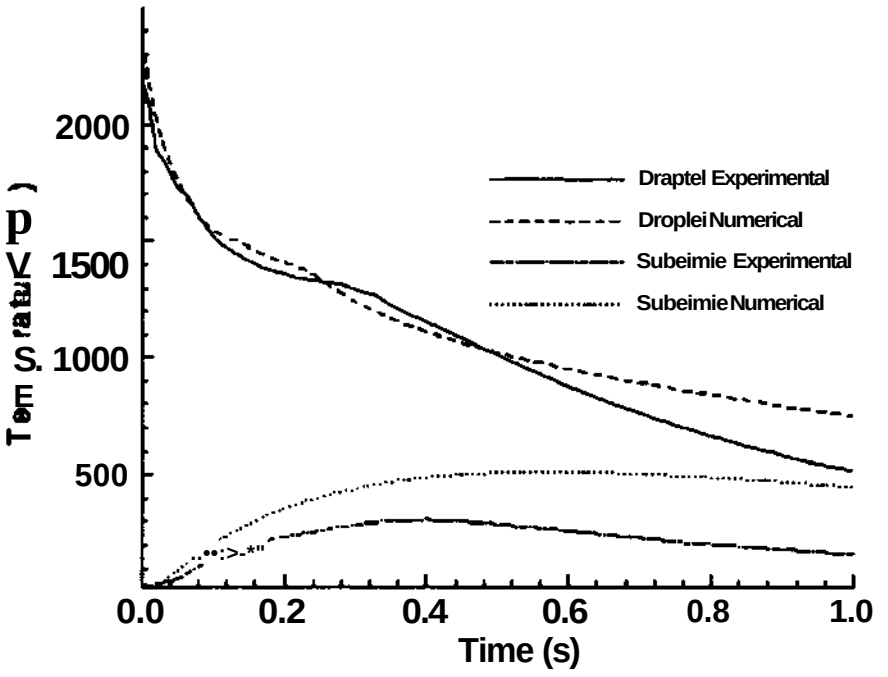


Figure 4. Experimental and Numerical Temperature Histories of Carbon Steel Microcasting Droplet and Substrate.

IV. Interface Remelting

Achieving bonding by the partial remelting of the substrate is critical for building metal structures with high strength bonding between sections, but a very limited alloying zone (i.e., in the mm range). In contrast, the support/primary material interface requires a bond which is strong enough to withstand cutting forces only, but does not require a full strength metallurgical bond. In fact, substrate remelting must be minimized to preserve the surface appearance of the microcast part. To create acceptable support/primary material interfaces, it is necessary that the materials have different melting temperatures and different thermal conductivities. The material with the higher melting temperature should have a lower thermal conductivity, and vice versa. For material combinations which experience a small difference in melting temperatures and a relatively large difference in thermal conductivities, microcasting conditions can be found such that each material will remelt only sections composed of the same material but not sections of the dissimilar material.

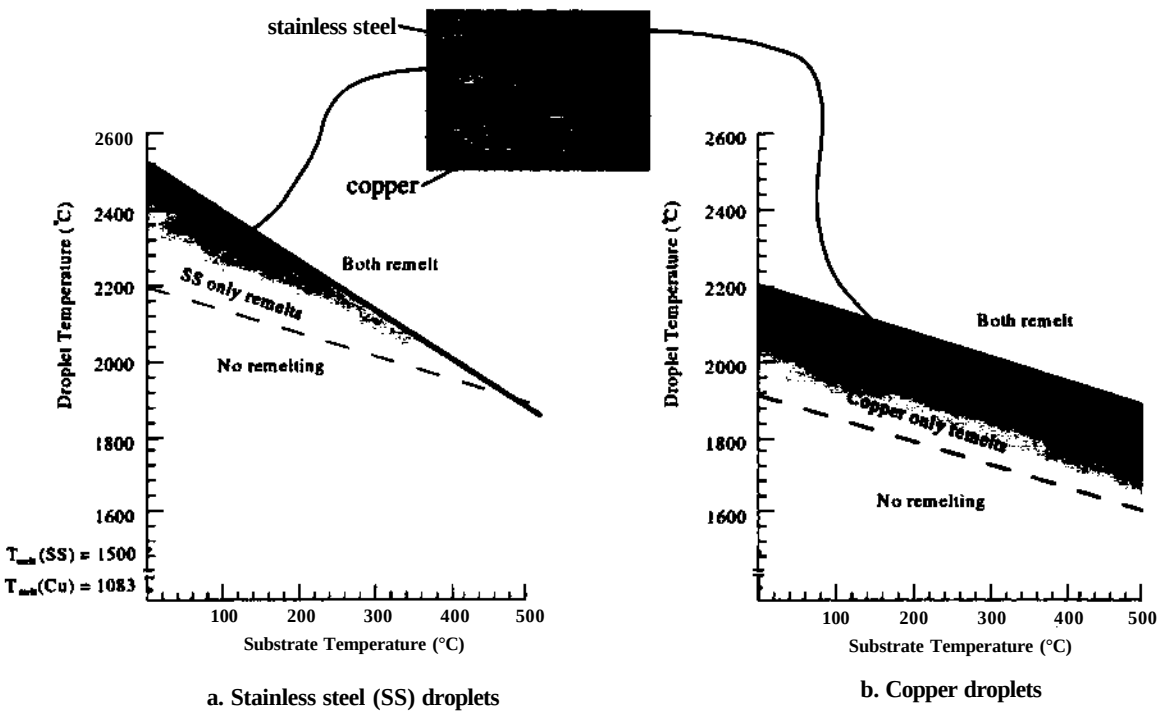


Figure 5. Remelting curves.

We have used the analytical Stefan problem (Carslaw and Jaeger, 1959) to determine the minimum initial droplet and substrate conditions to induce remelting for each combination of copper and steel droplets and substrates. The conditions needed to induce remelting for copper and stainless steel droplets and substrates are shown in Figure 5. The solid lines show the initial conditions needed for either substrate to remelt, and the dotted line indicates when only one substrate remelts. It is possible to avoid excessive remelting for either case of dissimilar materials due to the difference in thermal conductivity and diffusivity values between copper and stainless steel. A stainless steel droplet more readily causes stainless steel substrate remelting than copper, while a copper droplet remelts a copper substrate at lower temperature than a stainless steel substrate. For example, parts can be built out of 308 stainless-steel (Tmelt = 1500°C, k = 14W/m°C) with copper (Tmelt = 1083°C, k =

401 W/m°C) as the support material. In order to build overhang features, steel droplets can remelt the previously solidified steel, but not the higher thermal conductivity copper. The much greater conductivity of the copper substrate compared to the stainless steel substrate allows the droplet to solidify much faster, and therefore spreading less than for the stainless steel substrate. Interface remeking has also been studied via microstructural characterization (Amon, et al., 1996a).

V. Droplet Behavior

Efforts to improve our modeling accuracy require a better understanding of the fluid dynamic behavior of the droplet itself. We believe that minimizing voids depends on the ability of successive droplets to flow over and wet previous droplets, completely filling in the space between them. We have performed experiments to collect data related to the behavior of an individual droplet striking a flat substrate surface and solidifying (Schmaltz, et al., 1997). The data collected for the droplets include in-flight size, the transient spreading behavior, the final shape and height, and an estimated cooling rate. High speed photography has been used to capture in-flight images of the falling droplet and transient spreading, while still photography of the resulting solidified droplets allows us to quantify the effects of application parameters on final droplet shapes.

High speed photography allows us to measure the diameter of the falling droplet before impact and to observe the droplet motion upon impact with the flat substrate surface. Droplet diameter has been found to vary slightly as a function of plasma current. For both copper and stainless steel, droplet diameter decreases with increasing plasma power levels by about 5% over the total range of plasma power settings. Transient droplet spreading varies more than final solidified droplet shape, and this droplet fluid behavior before solidification is influenced by substrate roughness (arithmetic measure, R_a) as well as by the substrate material; droplets spread between 10% and 40% more over a smooth substrate surface (Ra values of 0.1 to 0.2 mm) compared to a roughened one (R_a values of 0.8 to 1.2 mm). Final droplet shapes are less influenced by parameter changes or deposit conditions, suggesting the importance of droplet fluid properties (surface tension) in the final droplet shape. In all cases, copper droplets undergo a greater degree of spreading than stainless steel droplets, though the reduction in the maximum transient spreading is more pronounced for stainless steel than copper droplets.

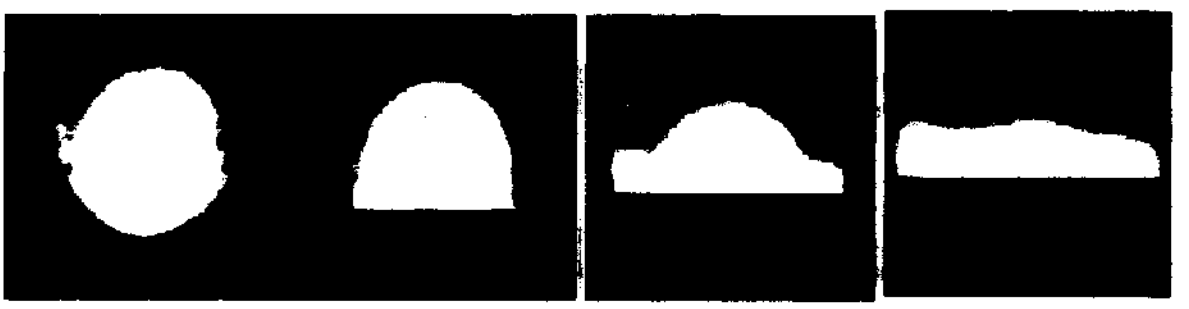


Figure 6, High Speed Photography of Stainless Steel Droplet Spreading (Images at time of impact, and 0.001, 0.002 and 0.003 seconds after impact).

The images shown in Figure 6 were recorded using a film speed of 5000 frames/second, yielding approximately 25 images of the droplet between first striking the substrate and reaching maximum initial droplet spreading after 0.003 seconds. Both stainless steel and

copper undergo several ensuing droplet oscillations before final solidification, which concludes in approximately 0.1 seconds. In addition to providing a basis for verification of the numerical model results, this filming also gives critical information on transient droplet/substrate contact angle during spreading.

VI. Conclusions

The SDM microcasting process has been developed to the point that we are able to manufacture complex geometric shapes from CAD models, using 308 stainless steel as the primary material and copper as the sacrificial material. Voids in the deposit have been reduced through the application of a experimental data gathering approach that uses Bayesian statistics, enabling us to locate the process design space that gives the best quality parts while performing fewer experiments. We are continuing to investigate the underlying causes behind voids, determine the best way to eliminate them, and develop a systematic representation of the parameter design space.

From our ongoing research we have gained significant understanding of the initial conditions present with microcasting, and the effect that process parameters have on these initial conditions. We understand the conditions needed to create remelting at the interface for an improved metallurgical bond, and these conditions are achieved by microcasting. We also understand the interaction at the interface when dissimilar materials are joined. Early numerical models have been partially successful in predicting thermal and mechanical stress behavior, affirming the remelting behavior predicted by our analytical calculations, and matching the experimental cooling histories with the thermal model results at the centerline droplet region during the early stages of cooling. Our current efforts are directed towards improvements in these simulations, including multi-dimensional modeling, the inclusion of fluid dynamic behavior, and thermo-mechanical modeling of the stresses based on the improved thermal models.

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