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Bulk metallic glass casting investigated using high-speed infrared monitoring and complementary fast scanning calorimetry

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ABSTRACT

This study describes a method which has been developed to monitor flow and cooling during casting using a high-speed infrared camera. The spatial and temporal resolutions were 60 µm and 1 ms, respectively. Calibration was performed to obtain the local, quantitative temperature history of a wedge-shaped specimen after post processing. Depending on microstructure (amorphous vs. crystalline) a temperature measurement accuracy of ±3 K or ±5 K was achieved. The temperature data recorded for a low-melting Au-based alloy during casting were compared thoroughly with its crystallization kinetics. The high-speed infrared measurements correlate well with fast differential scanning calorimetry (FDSC) results. This emphasizes the great potential of both techniques for studying fundamental processes which occur during casting.

1. Introduction

Bulk metallic glasses (BMGs) are exceptional candidates for small (mm- to cm-sized) high-precision parts subjected to mechanical loading [1–3] because of their high strength, low modulus, high elastic energy density, and potentially good dimensional accuracy due to low surface roughness compared with their crystalline counterparts [4–8]. Near-net-shape casting of BMG parts would be an economical processing route. However, in order to vitrify the melt it must be cooled sufficiently quickly to temperatures below its glass transition T_g. The minimum cooling rate required to achieve this is frequently called critical cooling rate $\dot{T}_{\mathrm{crit}}$. Various achievements in alloy development led to many types of glass-forming alloys which show a general decrease in $\dot{T}_{\mathrm{crit}}$ [8]. The critical cooling rates of BMGs have been determined using, for example, time-temperature-transformation (TTT) diagrams [9] or analytical expressions calculating $\dot{T}_{\mathrm{crit}}$ from characteristic casting geometry [10–12] or were measured directly by varying constant cooling rates using fast differential scanning calorimetry (FDSC) [13,14]. These values can be used to rank BMGs according to their glass-forming ability. However, from a processing point of view they are not sufficient for optimizing the mold geometries to create sophisticated cast parts. Simply quenching the melt as fast as possible to obtain a glass can produce casting defects such as flow lines or melt seams, i.e. cold shuts [15], which negatively affect part performance. Moreover, fast quenching hinders accurate mold filling because of early freezing, leading to incomplete filling. Instead of maintaining the highest cooling rates it would be more desirable to maximize the processing window, i.e. the time during which the melt can flow and still vitrify. Studies which focus on improved mold filling are scarce, but confirm the potential for near-net-shaping via casting, if the processing window is maximized [1,11,16–20]. Thermal history during BMG casting has been studied by inserting thermocouples into the mold cavity [11,21,22]. However, except for a local picture of the temperature evolution at the thermocouple locations with time, this method leaves some questions unanswered, because thermocouples have rather low spatial resolution, affect the flow, and are prone to thermal lag due to their non-zero mass and heat capacity [23].

High-speed infrared (IR) monitoring (or: high-speed thermography) has become a powerful technique for studying thermal processes up to megapixel resolution and kHz recording frequencies [24,25]. It was used to study in detail the deformation behavior of BMGs in the inhomogeneous flow regime [26–30]. Recently it has also attracted attention in the area of millisecond heating before thermoplastic forming [31,32], and in semisolid forging [33] of BMGs and BMG composites. In this contribution, we present the prerequisites for deploying high-speed IR monitoring

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to study fast casting processes using the example of wedge-shaped BMG casting. Filling and cooling have been recorded with 640 px × 144 px at 1000 fps, i.e. at a spatial resolution of approx. 60 μm and a temporal resolution of 1 ms. The thermal history for casting of a Au-based BMG was recorded using high-speed IR monitoring after setting up a feasible calibration route. The same low-melting temperature alloy ($T_m \approx 450\,^\circ C$) was also comprehensively studied using FDSC [13,14,34].

2. Experimental

The $Au_{64.25}Cu_{11.54}Ag_{7.41}Si_{16.80}$ pre-alloy [35] was prepared from high-purity raw elements – Au (99.99%), Ag (99.9%), Cu (99.99%), and Si (99.999%) – in an induction furnace under high-purity (6N) Ar atmosphere using alumina crucibles. For the IR measurements, the melt was drop-cast at 600 °C into a copper mold, which was heated to 50 °C (Fig. 1a). Here, after flowing through a vertical sprue, the melt enters a wedge-shaped cavity horizontally (see Fig. 1b) in order to prevent droplet formation and increased turbulence. The mold was oriented perpendicularly to an IRCAM Millenium 327k S/M high-speed infrared camera. The optical path between the mold and the objective lens of the camera was thoroughly shielded and the surfaces were coated with a high-emissivity paint to reduce reflections (Fig. 1c). The mold itself was covered by a sapphire wafer (Fig. 1d) which is IR-transparent in the observation wavelength interval of 4.30 μm to 4.75 μm (limited by a high-T bandpass filter). The filling and subsequent cooling processes were recorded at a frame rate of 1000 fps and a resolution of 640 px × 144 px. The appearance of the as-cast part is depicted in Fig. 1e. A decline in the degree of luster from the tip of the wedge towards the inlet is clearly visible to the naked eye.

By default the IR camera output would only yield black-body-like emission data (T_{IR}; emissivity, $\varepsilon \approx 1$), based on the factory calibration settings. Therefore a second radiation calibration was performed to ensure that quantitative temperature information could be obtained from the thermograms recorded [36]. Because the emissivities of the metallic glass and its crystallized counterpart are generally different and are not necessarily constants [37,38], two individual calibration curves, for the amorphous and crystalline regions, were generated. A graphite-shielded thermocouple (type K) was immersed in the melt and its signal was recorded during cooling simultaneously with T_{IR} captured for the equilibrium and undercooled liquid (up to 27.5 K undercooling with respect to the onset of melting). In the low-temperature regime (i.e.

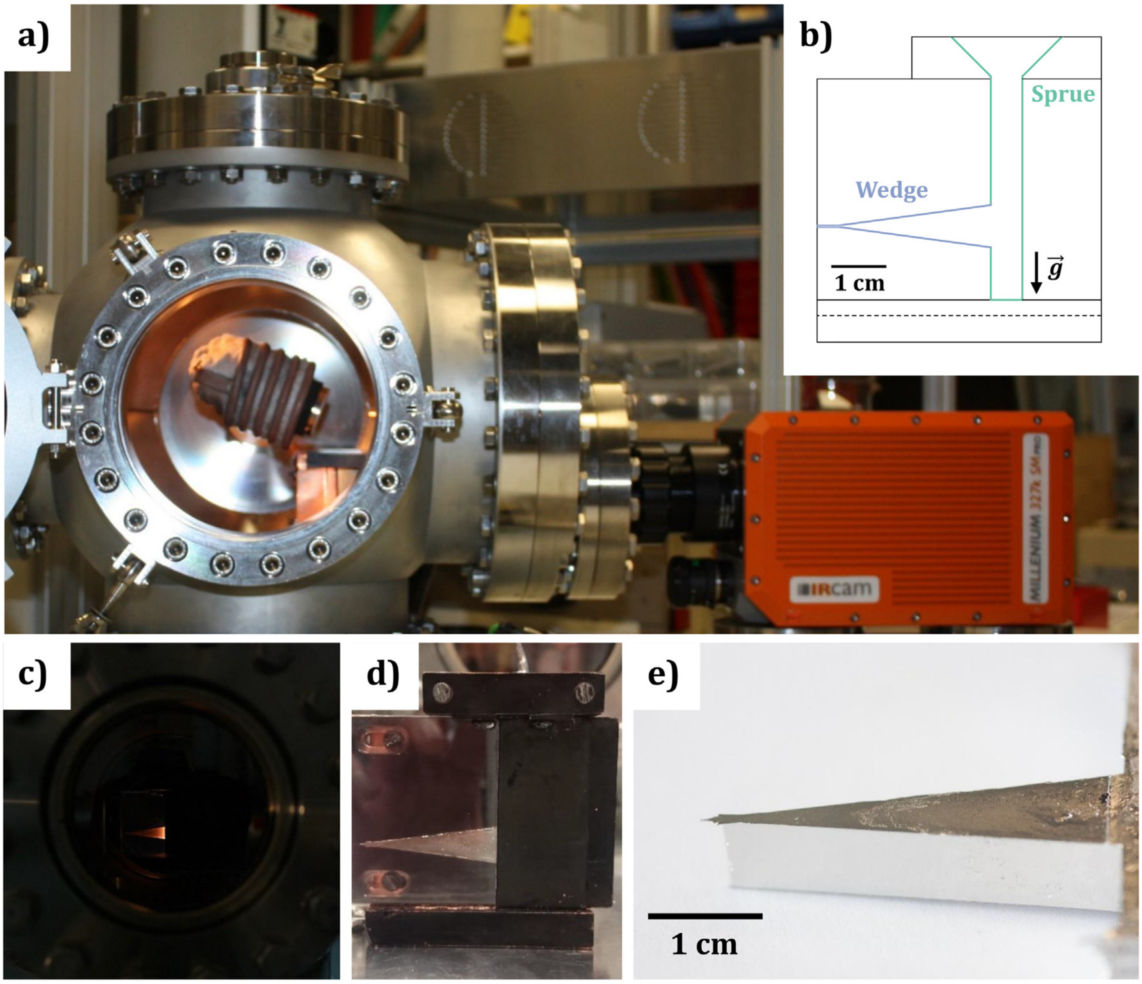

Fig. 1. Experimental setup for high-speed IR monitoring. (a) A drop-casting furnace involving inductive heating and a copper mold was modified for high-speed infrared imaging (IR camera seen on the right). (b) Schematic drawing of the copper mold consisting of a vertical sprue and a horizontally aligned wedge. (c) Shielding the coated optical path ensures reflection-reduced measurements. (d) The front of the mold cavity is covered by IR-transparent sapphire wafers. (e) A decline in the degree of luster from the tip of the wedge towards the inlet is visible to the naked eye.