A process for making lightweight cast-steel armor

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T he U.S. Bureau of Mines has developed a new method of making armor plate for military vehicles. The process was developed from the expendable pattern casting process (EPC) because it is ideally suited to making slot configurations required by the design of the new armor. While the advantages and economics of the EPC process were documented for casting aluminum,[1] it had not been used to make steel castings.

The new armor plate, designated P-900, is ballistically as effective as solid armor at equivalent thicknesses, but weighs 45% less. The armor has numerous oval-shaped slots in a regular array (Fig. 1). The slots are at an angle to the frontal plane of the plate. This design is referred to as "add-on" or "stand-off" because it allows the armor to be spaced several inches away from the vehicle. When hit, P-900 causes a projectile to shatter into smaller pieces, each of which has only a portion of the total energy of the whole projectile. The small pieces have insufficient mass and velocity to penetrate the vehicle hull.

P-900 armor offers many advantages: It is more efficient to transport, offers greater support economy, improves maneuverability, is easier to repair, and reduces vehicle fuel consumption. P-900 also is readily replaceable in the field, and its lightweight properties allow it to be retrofitted on most military vehicles without requiring a larger powertrain.
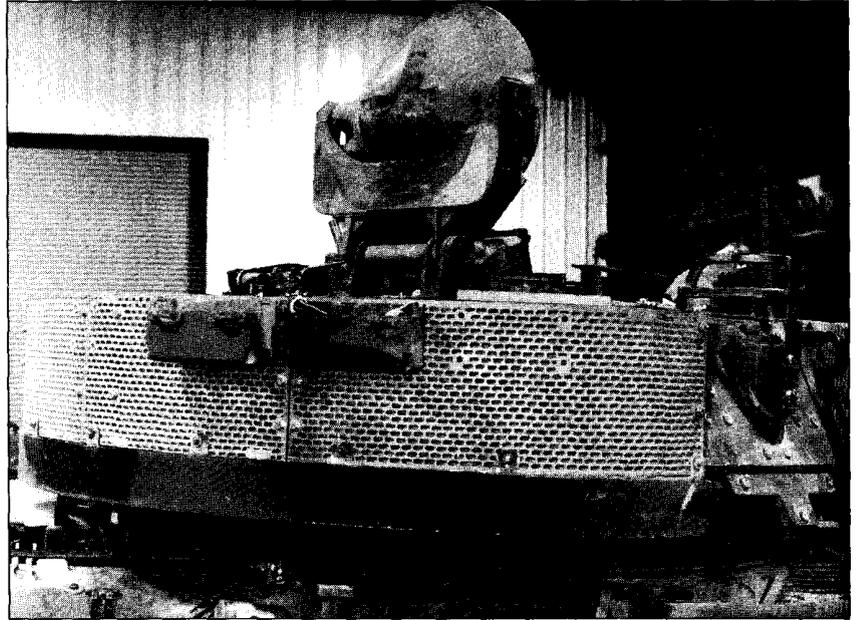
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Fig. 1 — P-900 steel stand-off armor, produced by the expendable pattern casting (EPC) process, is installed on a vehicle turret. It weighs 45% less than solid armor.

Basics of the EPC process

The P-900 slot configuration represents a complex manufacturing problem. The multiple, angled slots cannot be fabricated easily by punch-pressing rolled plate. Both investment casting and machining could be used to fabricate the armor, but are too expensive.

U.S. Bureau of Mines researchers selected the expendable pattern casting (EPC) process because it is ideally suited to make the slot configuration. In the EPC process, molten metal is poured directly into a polystyrene pattern that is embedded in unbonded sand. The pattern vaporizes, and the metal assumes the pattern's configuration. Cores are eliminated; and simple polystyrene shapes may be glued together to make a more complex pattern. Sand binders and sand preparation equipment are unnecessary, pattern and part drafts are reduced, parting lines are eliminated, post-casting cleaning is easier, and patterns
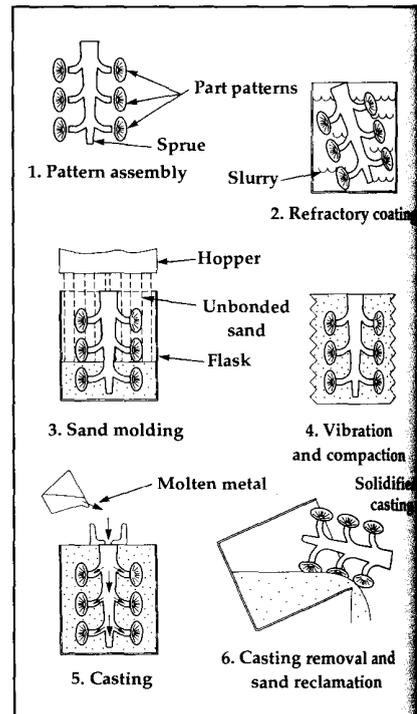

Fig. 2 — The EPC process, originally developed for casting aluminum, has been adapted for forming P-900 steel armor.

may be oriented within molds in a variety of positions to increase options for casting feeding and progressive solidification. Figure 2 shows the process steps.

While most problems with the EPC process using aluminum have been resolved, aluminum EPC techniques are not wholly transferable to steel. The replacement of a pattern by molten aluminum during pouring is slow, and the pattern and aluminum are in constant contact.[2] With steel, the pattern tends to liquify and evaporate as soon as hot metal enters the mold.[3] Molds may collapse well before the steel is available to replace the pattern. Unique casting defects are likely if pattern byproducts are not evacuated before the liquid steel can replace the pattern. Moreover, steel castings tend to be larger than aluminum castings, making pattern handling more difficult, especially if parts have thin walls or extended sections.

Modifying the process for steel

To successfully cast the steel armor, three innovations were added to the EPC process: Double-walled sand flasks were developed for the application of vacuum to sand molds; continuous narrow-necked feeding systems were used to deliver metal to all casting sections and to permit the casting of thin walls; and fixtures were designed to prevent pattern damage and to hold critical casting tolerances.

At normal casting temperatures, molten steel will not flow through the long, narrow webs and passages of the P-900 against the resistance of the pattern and pattern gases within the mold. With no means to enhance flow, frequent misruns can be expected. The application of vacuum to the mold forces the flow and helps ensure complete filling. The vacuum also provides a means for collecting and disposing of gases, adds rigidity to the mold, and prevents mold cavity collapse.

Double-walled steel molding flasks (Fig. 3) are required to apply the vacuum. The inner walls consist of fine-mesh screens that are glued to perforated metal sheets. The screens confine the mold and prevent molding sand from entering the vacuum system. The flask is closed following pattern inser-

tion, sand molding, and sand compaction by covering the mold with a sheet of polyethylene film.

Initially, with conventional bottom gating methods and standard runners and gates, metal failed to flow to all sections of armor plates measuring as small as 30 × 30 × 1.5 cm (12 × 12 × 0.6 in.). Even with the feeding assistance of vacuum, complete filling followed only after feeding distances were shortened to 8-10 cm (3-4 in.) by gating directly into the frontal surface of the part.

The gating system was designed for easy removal by knock-off. A primary runner extends along the length of the casting at the bottom. Square secondary runners, measuring 1 cm (0.4 in.) on a side, connect to the primary runner at right angles and span the entire width of the plate at intervals of 15 to 25 cm (6 to 10 in.) along the length. The secondaries are connected to the
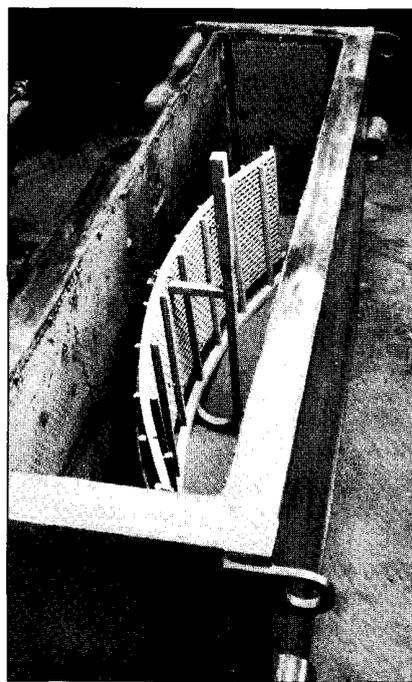

Fig. 3 — A P-900 fixture and pattern are placed in a flask prior to molding.
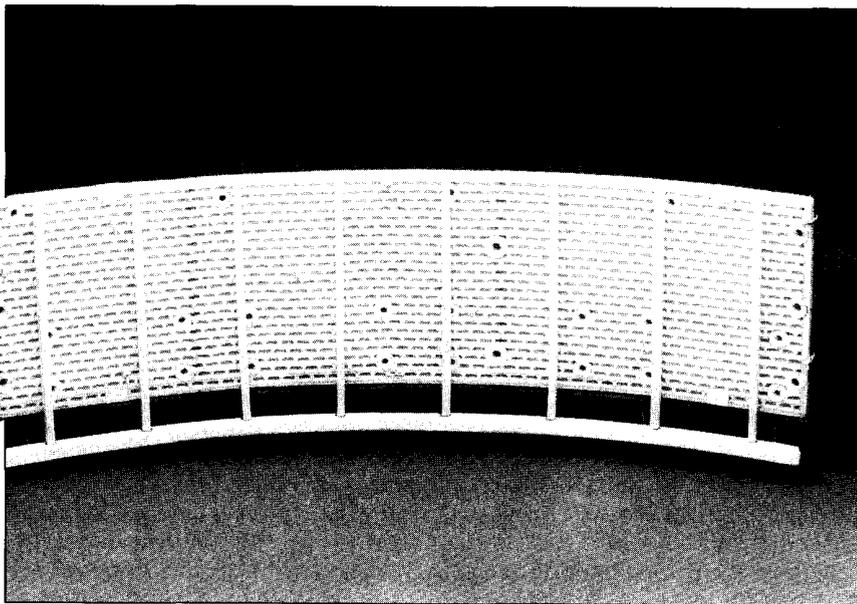

Fig. 4 — Runner and gating system for a P-900 armor plate section is designed for easy removal by knock-off. A primary runner extends along the bottom of the casting.

webs between the slots by short gates measuring only 3 mm (0.1 in.) thick (Fig. 4).

Reusable fixtures are needed to ensure curved armor plate contours. The patterns can be flexed to the fixture and attached with string. The fixture and pattern are inserted into the flask, and the flask is filled with unbonded sand and vibrated for compaction. The fixture prevents distortion of the pattern by sand currents. The positioning of a pattern and fixture in a

flask prior to sand addition is shown in Fig. 3.

In comparison with castings produced by other processes, EPC steel casting surfaces are relatively clean because of the absence of sand binder and binder-related defects. All castings can be heat treated using normal quench-and-temper cycles.

Casting problems and defects

One of the reasons the EPC process normally is not used for

steel casting is that the steel absorbs carbon from the pattern during pouring.[4] This carbon pickup can occur by one or more mechanisms. Styrene vapors can condense on the molding sand next to the casting. Carbon from the condensed vapors then diffuses back into the casting surface during solidification, forming a case. In some instances, the case could be beneficial, for example during heat treatment, when surface carbon normally is depleted. Carbon also can be absorbed from pattern gases that are in contact with advancing molten steel surfaces. Additional heavy concentrations of carbon can result from liquid or solid styrene that falls into the steel. These concentrations are unpredictable and cause unacceptable inconsistencies that prevent EPC from becoming a general process for steel casting.

In the P-900, however, carbon pickup is insignificant along the thicker lower edges and sides of plates where molten metal movement and flushing are greatest. Concentrations rise toward the center of the plates by as much as 0.1% from a furnace carbon level of 0.3%. While a 0.1% C fluctuation would ruin most castings, P-900 ballistic properties are insensitive to carbon content over a range of 0.25 to 0.4%.

Shrinkage allowance: The rule-of-thumb allowance for steel casting shrinkage is 0.25 in./ft (about 20 mm/m), or 2.1%. The average shrinkage of flat P-900 castings that measure approximately 37 × 75 cm (15 × 30 in.) is 2.3 to 2.4%. One explanation for the greater shrinkage with the modified EPC process is that the vacuum acting on the sand compresses the pattern and mold cavity when the pattern is heated during pouring. In some castings, the shrinkage is slightly higher in the vertical direction than in the horizontal direction. The discrepancy is due to mold movement in the vertical direction brought about because the top surface of the flask is a plastic film that flexes downward toward the pattern when the vacuum is applied. All of the horizontal forces on the pattern are equal.

Further dimensional discrepancies occur when polystyrene patterns are bent to the curvatures of a fixture. Flat patterns extend on the outside surface and compress on the inside surface. Consequently, if the patterns have been measured in a flattened position, the resulting shrinkage of the castings will appear greater in the stretched direction. The shrinkage of the casting shown in Fig. 1 was 1.5% in the horizontal (curved) direction and between 1.8 and 2.2% in the vertical direction. The total dimensional change reflects normal steel casting shrinkage, pattern stretching, and compression by the vacuum. Variations among producers could be expected from several additional sources, including the degree of flask vacuum, the efficiency of sand compaction, the size and distribution of sand, and the design of the flask.

Pouring temperature: Because metal flow is related to temperature, the pouring temperature for thin-wall castings is critical. The occurrence of misruns when all other variables were controlled, attested to the importance of pouring temperatures with large P-900 castings. The low-alloy steel used for most of the successful castings was tapped from an induction furnace at a minimum of 1665°C (3030°F). Temperature losses from ladle transfer and from the endothermic destruction of polystyrene were estimated to be nearly 80°C (145°F). The liquidus of the low-alloy steel is 1560°C (2840°F).

Hot tears: Hot-tear-like defects occurred opposite the gates on P-900 castings that were curved, but not on castings that were flat. On some castings, the defect was prevalent in as many as 20 webs, always in the vertical direction, while in others, tears appeared in only three or four webs. Although pouring temperatures were implicated, the hot tears may have been precipitated by more traditional causes, such as mold constraint. In any case, hot tears were largely eliminated by adding thickness to selected webs and by removing the extra material in finishing.

Amount of vacuum: The addition of vacuum to molds is crucial to allow complete filling of P-900 castings. However, vacuum accelerates metal movement and increases metal turbulence. Metal must be poured accurately and rapidly into a vacuum to prevent the development of vortexes and the ingestion of air. On solid plates (without the P-900 design), the presence of fewer surface defects is associated with less vacuum.

One other common vacuum-related defect has the appearance of shallow "worms" that form when styrene liquid concentrates on the inside of the cavity wall. The concentrate eventually is consumed, but not until after it leaves its imprint on the casting surface.

Without vacuum, more heat is transferred throughout a longer filling period. Pattern gases and mold walls are hotter, and liquefaction is less likely. The significance for any EPC steel casting is that casting should be done with the least amount of vacuum assist necessary to attain complete filling. The amount of assist needed depends on several variables, with casting size and wall thickness being the most important. ■

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