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Casting P-900 Armorplate by the Expendable Pattern Casting Process

By J. S. Hansen and P. C. Turner

UNITED STATES DEPARTMENT OF THE INTERIOR



BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C degree Celsius

mm millimeter

cm centimeter

pct percent

m meter

CASTING P-900 ARMORPLATE BY THE EXPENDABLE PATTERN CASTING PROCESS

By J. S. Hansen¹ and P. C. Turner²

ABSTRACT

The U.S. Bureau of Mines developed a system for casting unique, slotted steel armor by modifying the conventional expendable pattern casting (EPC) process that is normally used for making aluminum castings. Three innovations were added to the EPC process to make the successful adaptation: (1) Vacuum was applied to sand molds, (2) continuous narrow-necked feeding systems were used to permit the casting of thin walls, and (3) fixtures were designed to prevent pattern damage and to hold critical casting tolerances. Potential problems and defects are described.

¹Metallurgist.

²Project supervisor.

Albany Research Center, U.S. Bureau of Mines, Albany, OR.

INTRODUCTION

Constant research and development on armorplate for armored military vehicles is required to shield troops against new ballistic threats. Armor obsolescence occurs whenever new projectiles are invented to penetrate or destroy current state-of-the-art armor. The armorplate (designated P-900) described in this report is configured with numerous slots in a regular array (fig. 1). The slots are oval shaped and at an angle to the frontal plane of the plate. The webs separating the slots are about 40 mm thick. P-900 is as effective antiballistically as solid armor at equivalent thicknesses but weighs 45 pct less.

P-900 is installed by hanging the plates away from a vehicle, thus giving rise to the terms "add-on" and "stand-off." The armor works by shattering a projectile that has been fired at the vehicle into many smaller pieces, each of which has only a portion of the total energy of the whole

projectile. After encountering the P-900, the fractured pieces of the projectile have insufficient mass and velocity to penetrate the hull of the vehicle.

Vehicles that are fitted with lightweight armor have significant benefits, including more efficient transportability, greater support economy, higher maneuverability, ease of repair, and lower fuel consumption. The P-900 armor can be replaced promptly to repair conflict-damaged armor. In the case of retrofits for existing vehicles, original engines do not require upgrading.

The U.S. Army Tank and Automotive Command (TACOM) requested that the U.S. Bureau of Mines assist in research on P-900 armor because of previous Bureau research on innovative expendable pattern casting (EPC) methods of casting steel.

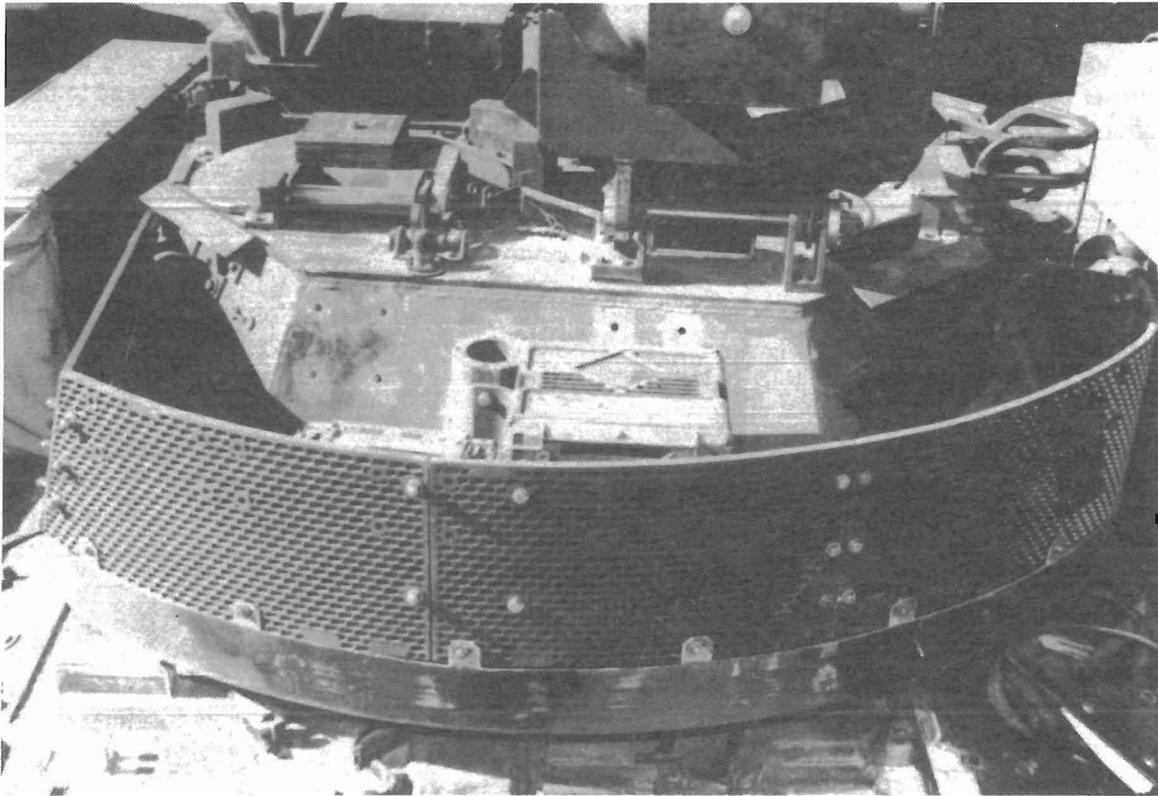


Figure 1.—P-900 castings for stand-off armor (installed on vehicle) showing angled slot configuration.

MANUFACTURING ALTERNATIVES AND THE EPC PROCESS

The P-900 slot configuration, in the form of a bustle for turret protection, presented a complex manufacturing problem. The multiple angled slots could not be easily fabricated by punching rolled plate on a press. Conventional methods of casting also were not adaptable to the slot arrangement because pattern lift off could not be made perpendicularly to the plane of the plate. Investment casting and machining were both conceivable, but far too expensive.

The EPC process was selected because it was ideally suited for the slot configuration and because its economies have been documented in the casting of aluminum (1-3).³ However, the process has not been used to manufacture steel castings. TACOM approached the Bureau with the problem because of the Bureau's past research in casting steel with the EPC method.

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 (4). Each casting requires a new pattern. Figure 2 shows the process steps: (1) pattern assembly, (2) refractory coating, (3) sand molding, (4) vibration and compaction, (5) casting, and (6) casting removal. Process advantages include elimination of cores, an option of gluing simple pattern parts together to make a more complex whole, elimination of sand binders and sand preparation equipment, reduction of pattern and part draft, elimination of parting lines, reduction of postcasting cleaning, and freedom to orient patterns in molds in a variety of positions to increase options for casting feeding and progressive solidification.

MODIFYING THE EPC PROCESS FOR STEEL

While most problems in casting aluminum using the EPC process have been resolved, the techniques for aluminum EPC are not entirely transferable to steel EPC, and additional problems are encountered. The replacement of a pattern by molten aluminum during pouring is slow, and the pattern and aluminum are in constant contact (5). With steel, the pattern tends to evaporate as soon as hot metal enters the mold (6). Molds may collapse well before metal is available to replace the pattern. Steel castings tend to be larger than aluminum castings, and therefore, the patterns for steel castings are less rigid. Pattern handling is more difficult, especially if parts have thin walls or rangy sections. Unique casting defects are likely if pattern residues are not eliminated before the liquid steel takes the pattern's place.

³Italic numbers in parentheses refer to items in the list of references at the end of this report.

The P-900 armor was successfully cast by modifying the EPC process for aluminum casting and adapting it to steel. Three innovations were added to the EPC process for aluminum to make the successful adaptation: (1) Double-walled sand flasks were developed for the application of vacuum to sand molds, (2) continuous narrow-necked feeding systems were used to deliver metal to all casting sections and permit the casting of thin walls, and (3) fixtures were designed to prevent pattern damage and to hold critical casting tolerances.

EPC patterns are constructed by expanding polystyrene beads with pentane (no chlorinated fluorocarbons (CFC's)) (7). Commercially, patterns are made to the required size, but for development purposes in this study, patterns were made from a common preform containing the slotted configuration. The steps for making the finished pattern are depicted in figure 3.

At normal casting temperatures, molten steel would not flow into the long, narrow slot webs and passages of the P-900. With no means to enhance the flow, the result was frequent misruns. The application of vacuum to the mold provided the necessary flow enhancement and ensured complete filling. The vacuum aided metal feeding

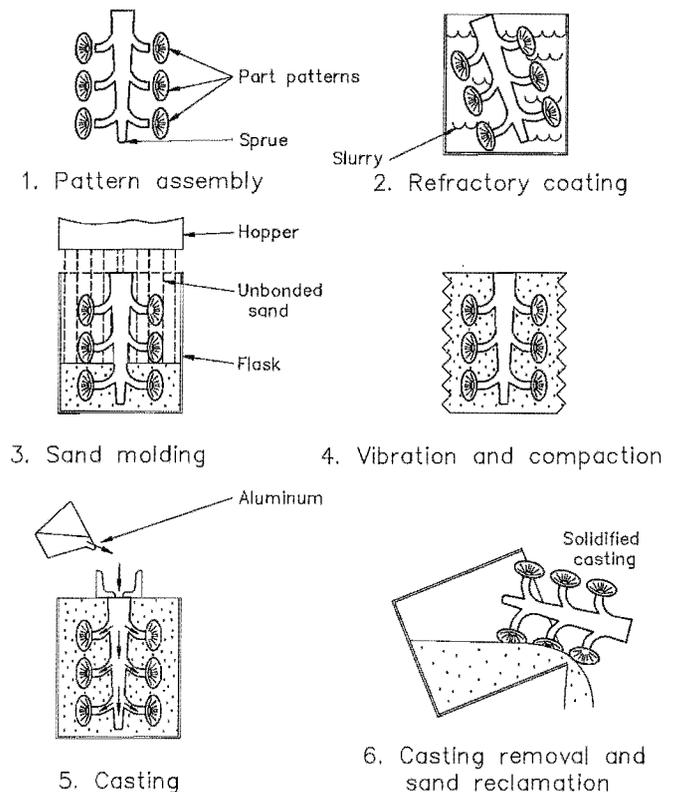


Figure 2.—EPC process steps.

by effectively increasing the pouring height equivalent to about 1.5 m. In addition, the vacuum collected vaporized pattern gases for disposal, added rigidity to the mold, and prevented cavity collapse.

Double-walled steel molding flasks were constructed for vacuum application. The inner walls were spaced about 7 cm from the outer walls. The inner walls consisted of fine-mesh screens that were glued to perforated metal and subsequently bolted to appropriately spaced ribs in the flask. The screens confined the mold and prevented molding sand from entering the vacuum system. Following pattern insertion, sand molding, and sand compaction, the flask was closed by covering the top of the mold with a sheet of polyethylene film. The plastic was sealed to the flask with grease. Large-diameter hoses connected the flask with a vacuum system containing a large surge tank. Systems without the surge tank appear to lack sufficient capacity for immediate evacuation. Even with the surge tank, a gauge on the flask showed an initial 20-pct loss of vacuum upon pouring. Recovery occurred within seconds. Vacuum was discontinued after pouring.

Initially, when conventional bottom gating methods and standard runners and gates were used, metal failed to flow to all sections of slotted armorplates measuring as small as 30 by 30 by 1.5 cm. Even with the feeding assistance of vacuum, complete filling was achieved only after feeding distances were shortened to 8 to 10 cm by gating directly into the frontal surface of the part. Normally, the large number of gate attachments and subsequent gate removal operations would involve considerable labor and expense. The problem was solved by extending a primary runner along the length of the casting at the bottom and constructing square secondary runners, measuring 1 cm on a

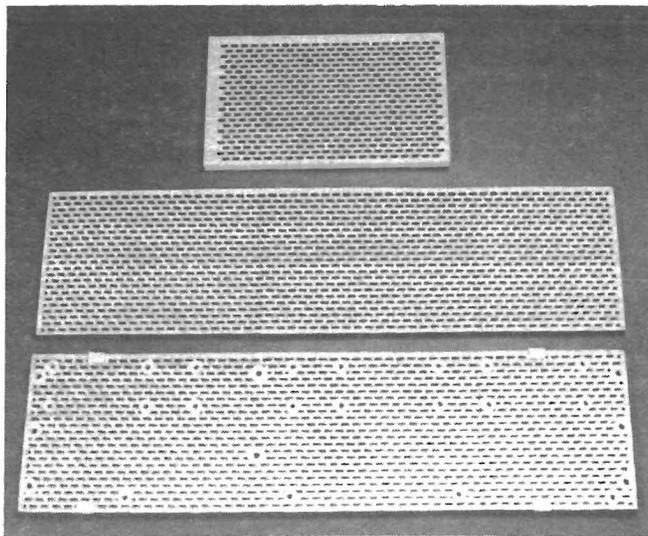


Figure 3.—Building useful P-900 pattern from standard preform. Top, Standard preform; middle, P-900 plate pattern constructed from preforms; bottom, P-900 plate pattern, including mounting holes.

side, that spanned the entire width of the plate at intervals of 15 to 25 cm along the length. The gating system is shown in figure 4. The runners were connected to the webs between the slots by 3-mm-wide gates. Delivery of hot metal through the relatively large secondary runners to the much narrower webs of the plate ensured complete filling of castings and prevented premature mold collapse. When solidified, the runners and gates were easily removed with a hammer and required little finishing.

Fixtures were made containing the desired armorplate contours. A typical fixture is shown in figure 5. The patterns were flexed to the fixture contour and attached with string. The pattern and fixture were dipped in a slurry of fine silica with a binder, as shown in figure 6. Coatings helped to keep intact the cavity that resulted after the pattern evaporated during pouring and provided a better surface finish. The slurry was dried before the pattern was molded in a vacuum flask. The reusable

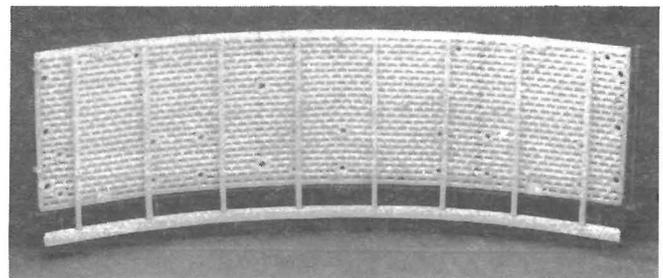


Figure 4.—Runner and gating system for P-900 armorplate section.

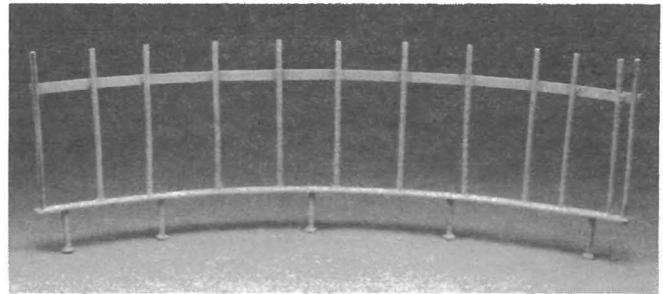


Figure 5.—Fixture to provide rigidity and curvature to flat P-900 pattern.

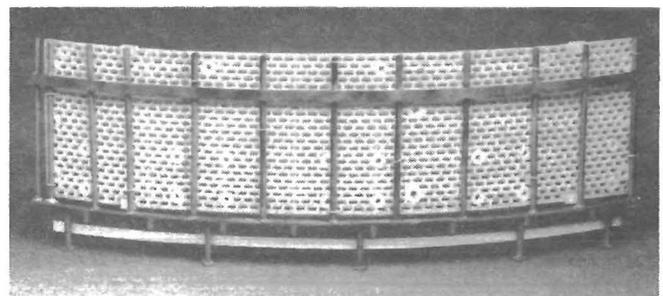


Figure 6.—P-900 pattern attached to fixture with string.

fixtures were easily inserted within a flask along with a pattern. Figure 7 shows positioning of the coated pattern and fixture in the flask prior to sand addition. The flask was filled with unbonded silica sand and vibrated for compaction. The fixture prevented distortion of the pattern by sand currents. The open top of the flask was sealed for vacuum and evacuated. A sand pouring basin was placed on the top of the plastic with its opening adjacent to the sprue.

After being poured, the casting was allowed to solidify and cool before it was removed from the flask. The unbonded sand required no treatment other than cooling before recycle. Casting surfaces were relatively clean, in comparison with castings made with other processes, because of the absence of sand binder and binder-related defects. The gates were detached by impact with a hammer. Portions of gating that remained on the casting, although nearly insignificant, were removed by grinding. The castings were heat-treated using normal quench and temper cycles.

A P-900 outer hatch plate, shown in figure 8, was a second application of the modified EPC process. The hatch casting illustrates the complexity and detail that are possible with the process. Even the bead structure of the polystyrene pattern is reproduced in the casting and is evident in many of the oblong slots shown in the photo.



Figure 7.—Fixture with pattern in flask prior to molding.

The procedure for making the outer hatch plate was similar to the procedure used for the bustle sets, except that in place of the welded fixture for the bustle, a sand core was made to conform to the inside dimensions of the hatch plate. The polystyrene pattern for the casting was built over the core by gluing pattern sections to the core. As with other P-900 castings, break-off gates and vacuum were used to ensure complete filling. A core and pattern with gates are shown in figure 9. The pouring procedure and cleanup for the casting were similar to those used to make the bustle castings.

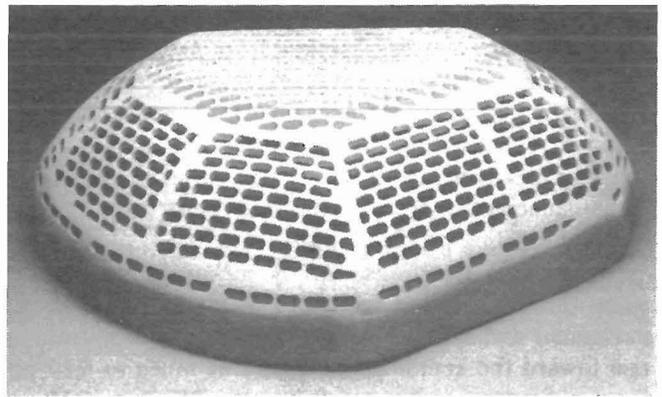


Figure 8.—P-900 hatch plate casting.

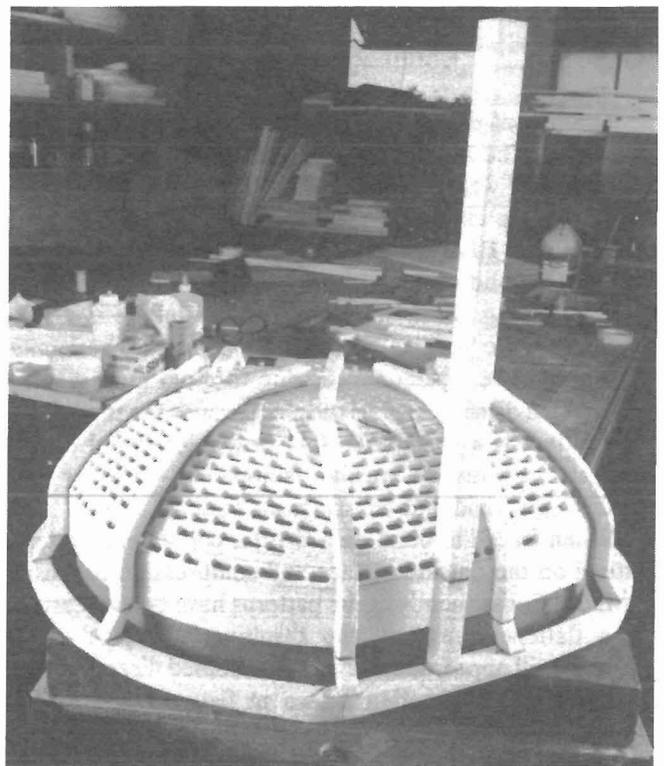


Figure 9.—Hatch plate pattern formed over sand core fixture with gating.

CASTING PROBLEMS AND DEFECTS

Carbon Pickup

One of the reasons the EPC process has not been used for steel casting is that the steel absorbs carbon from the evaporating pattern during pouring (8). The absorption may occur by several mechanisms: (1) Styrene vapors may condense on the molding sand next to the casting, and carbon from the condensed vapors may diffuse back into the casting surface after it solidifies, forming a case. In some instances, the case may be beneficial—for example, during heat treatment when surface carbon is depleted. (2) Carbon also may be absorbed from pattern gases that are in contact with the advancing molten steel surface. (3) Finally, heavy concentrations of carbon may occur from liquid or solid styrene that falls into the steel. These concentrations are unpredictable and cause the intolerable inconsistencies that prevent EPC from being considered as a general casting process for steel.

In the P-900 castings, carbon pickup is insignificant along the lower edges and sides of plates, where metal movement and flushing is likely greatest. Concentrations rise toward the center of the plates as much as 0.10 pct from a furnace carbon of 0.30 pct. While a 0.10-pct C fluctuation would ruin almost any other casting, P-900 ballistic properties are insensitive to carbon contents in a range of 0.25 to 0.40 pct.

Shrinkage Allowance

The rule-of-thumb allowance for steel casting shrinkage is 2.1 pct. The average shrinkage measured on flat P-900 castings that were approximately 37 by 75 cm was 2.3 to 2.4 pct. One explanation for the greater shrinkage with the modified EPC process is that the vacuum compresses the pattern and mold cavity when the pattern is heated during pouring. In some castings, the shrinkage is slightly greater in the vertical direction than in the horizontal direction. The discrepancy is due to mold movement in the vertical direction, which occurs because the top surface of the flask is a plastic film that flexes downward toward the pattern when the vacuum is applied. All other flask surfaces are rigid and constrain movement.

When forced to bend on a fixture, polystyrene 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 figure 1 was 1.5 pct in the horizontal (curved) direction and between 1.8 and 2.2 pct in the vertical direction. The total dimensional change reflects an amount for normal steel casting shrinkage plus an amount for pattern stretch.

In a comparison of shrinkage values for the same prototype parts from multiple foundries, shrink rates varied slightly from the values noted above, even though similar patterns from the same run were used in the comparison. Variations could be expected from several sources, including the degree of flask vacuum, the efficiency of sand compaction, the size and distribution of sand, and the design of the vacuum flask.

Pouring Temperature

Because metal viscosity is related to temperature, the pouring temperature for thin-wall castings is a critical factor. The fact that misruns were experienced in castings when all other variables apparently were controlled attested to the importance of pouring temperatures with large P-900 castings. Unfortunately, pouring temperatures for P-900 castings were difficult to measure because of the nature of the pouring process and essential safety precautions. The low-alloy steel that was used for most successful castings was tapped from an induction furnace at a minimum of 1,665° C. Temperature losses from ladle transfer and from the endothermic destruction of polystyrene were estimated to be nearly 80° C. The liquidus of the metal was 1,560° C.

Hot Tears

Hot tear-like defects occurred opposite gates on P-900 castings that were curved, but not on castings that were flat. On some castings the defect was prevalent in up to 20 webs, always in the vertical direction, while in other castings, tears appeared in only 3 or 4 webs. High pouring temperatures were implicated. However, the absence of the defect in flat castings suggested that the pattern may have fractured after it was stretched over the fixture prior to metal entry. The patterns were inspected and were found to be free of cracks before molding. In addition, several patterns that were carefully removed from flasks following molding and sand compaction also were found to be free of cracks. If pattern cracking occurred, presumably it happened when molten metal heated and weakened the polystyrene prior to evaporation. The hot tears may have been precipitated by more traditional causes such as mold constraint (9). In any case, hot tears were largely eliminated by adding thickness to the webs and by removing the extra material in finishing.

Amount of Vacuum

The addition of vacuum to molds was imperative to the complete filling of the castings shown in the figures. However, vacuum speeds metal movement, and consequently, turbulence is greater. Pouring must be

accomplished rapidly to prevent a vortex from developing in the sprue with the resulting ingestion of air.

Tests on solid plates (without the P-900 design) showed that fewer surface defects occurred with less vacuum. One common defect had the appearance of a shallow worm. The worm defects apparently formed when styrene vapors condensed and concentrated on the inside of the cavity wall. The condensate was consumed after it left its imprint on the casting surface.

Pattern evaporation and mold filling are more rapid with vacuum than without vacuum; without vacuum, greater heat transfer occurs during a longer filling period. Pattern gases and mold walls are hotter, and liquification is less likely. The significance for casting P-900 is that casting should be accomplished with the least amount of vacuum assist necessary to achieve filling. The optimum level of vacuum will depend on several variables, casting size being the most notable.

CONCLUSIONS

The EPC process can be used to make steel P-900 stand-off armor if several modifications to conventional EPC technology are implemented. In fact, EPC may be the only economical technology to make P-900. The modifications include the application of vacuum to molds to assist metal flow, continuous line-gate feeding systems to ensure hot metal delivery to extended thin-wall sections, and fixtures to prevent distortion while maintaining dimensional accuracy. The use of vacuum has negative aspects that can be avoided if the minimum vacuum needed to achieve complete filling is used.

Shrink rates are slightly greater than conventional shrink rates and may be greater in the vertical direction than in the horizontal direction. When flexed over fixtures, polystyrene patterns stretch. The amount of pattern stretch must be accounted for in the shrink rate. Pouring temperature is critical. Too high a pouring temperature will promote hot tears, but too low a temperature will result in misruns. Carbon pickup occurs in P-900 castings, but ballistic properties are independent of carbon levels over a relatively wide range.

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