Mandrel Design for Solid Propellant and Hybrid Rocket Motors

By William Colburn

Overview:

Casting a Solid Propellant Grain usually requires leaving a vacant core in the propellant, often of a complex shape. Composite Propellants, have by nature, an adhesive rubbery component which tends to adhere to common materials to be used for mandrels. In addition the blended propellant may be very sensitive to friction and shock. Those combined factors make the removal of mandrels a difficult and dangerous task.

In hybrid motors, the sensitivity to friction and danger is largely missing since the hybrid fuel component has no oxidizer, but the difficult extraction problem remains, particularly for larger motors. Note I say "largely" since even with a hybrid fuel grain, a highly metallized composition might react with a fluorinated release agent under high mechanical stress.

Requirements for a Good Mandrel Design:

Surface Finish- Early mandrels required a "mirror" finish for adequate removal characteristics. In addition a release agent was used on the surface, one which was lubricous with the composite propellant binder and did not react with any of the propellant components.

Aluminum was the material of choice as it was readily machined to the contour desired and was available in many off the shelf sizes. Later, this requirement was relaxed slightly as a baked Teflon™ finish or a thick coating of wax was employed for a release.

In the Aerojet method using a wax release, the coating was quite thick and the release was obtained by warming the propellant grain. The mandrel was then easily extracted hydraulically and remotely. One Thiokol design used a spiral mandrel rotated for extraction.

Tolerances- Not only should the mandrel be uniform and symmetrical (if so designed) but should also have provisions for centering in the casting condition. Eccentricity of the mandrel in the casing is directly related to total impulse reduction. Mandrels should have an "O" Ringed boss which mates to a receiver on the head end of the motor case or a pointed center which matches a conical well internal to the head end. This centering provision must be well designed to prevent intrusion of propellant which could be initiated during the mandrel extraction process. In the case of the mating conical surfaces, mechanical shock to the mandrel could cause initiation if any propellant intruded between the two conical surfaces. In no instance would threads be used which could be wetted by uncured propellant.

Surface Condition- The chemical condition of the surface of the mandrel should be such that the propellant binder is not adhesive to the mandrel. This is usually the purpose of the release agent. Chilling may also have the same effect bringing about release, particularly with a great difference in thermal contraction coefficients.

Release Agents- Teflon™ is the usual material used for a release agent. It may be a sprayed and baked on finish for greater durability or simply replenished after each use as a cold coating. Silicones have also been employed; Wax, too, as mentioned above.

Release agents must always be applied in a room dedicated to such an operation; the presence of silicones especially in other operations such as composite filament winding can be disastrous. The failure of a large composite tank for the X-33 program failed due to the inclusion, during manufacture, of a tiny piece of Teflon™. For a short run in a simple geometry, Teflon™ tape may be applied to the mandrel.

Coatings- A suitable coating can be applied in many ways; spraying followed by drying or baking, powder coating, brush application of a high solids-loading release agent, or dipping. Two coatings may be used. The first as a substrate for the second which is adsorbed or absorbed by the first.

One consequence of coatings which might contaminate the core is in the desensitizing the propellant grain to ignition. This is sometimes remedied by “scraping” the internal surface of the core. A story is told about an incident with a large (presumably 120 inch diameter motor) in which a small person was hired to scrape the core by walking the length of the grain. He was observed taking a break, sitting on the end of this gigantic grain, smoking a cigarette! This is a practice to be discouraged or watched from a vantage point a few miles removed. (The sarcasm should be obvious in my last remark)

Strength- Clearly the mandrel must be strong enough to withstand the stress of extraction. This may be many tons in the case of a large grain. Extraction typically requires a very high “breaking” force after which the mandrel is easily removed with much less force. Hydraulic rams are the typical choice as they have consistent controllable force and are non-electrical in operation, requiring special means for isolation of circuitry.

Steel is not used for mandrels because of the danger of sparking if struck. Aluminum is the usual choice having adequate strength, availability, and machinability.

Soluble Mandrels- Two types come to mind: a plaster variety which can be removed by a water jet and foamed mandrels which require a solvent. Certainly other materials could be successfully employed (stacked sugar cubes) which would be soluble and permit the solvent to readily penetrate the mandrel.

A foamed mandrel may be made with a central core so that on ignition it is removed thermally. This would be especially effective in a Hybrid Propulsion System.

Fusible Mandrels- Low temperature alloys such as Ceralloy™ have been used for casting mandrels. After the propellant has been cured, heating to below the boiling point of water will melt out the mandrel. Wax can also be used but will leave a coating on the interior of the core.

Collapsing Mandrels- It is not known if the Goodyear AirMat™ had been used as a mandrel (it is a rubber impregnated cloth with internal webbing to maintain a specific shape when inflated-used on an inflatable aircraft), but there is a patent assigned to CSD Division of Pratt and Whitney which uses a rubber membrane coated on a precision foam mandrel. When the propellant has cured, the mandrel is pressurized which collapses the closed-cell foam. The rubber membrane then falls free.

Sectional Mandrels- Widely used for complex shapes. The simplest is a hex bar stock with six square rods attached via a shearable cement (cyano-acrylate). The hex bar is twisted slightly after curing the propellant to effect a bond release from the six bars. The center hex is then removed easily followed by the six square bars. From this simple basic design one can extrapolate to the design of more complex geometries.

A three-dimensional shape such as may be required for a spherical motor could be made like a Chinese puzzle.

Active Mandrels- Here a foamed propellant is used as the core. Its ballistic properties are matched to that of the main grain so it serves as a gigantic igniter/initial burn. This was proposed in the early 60's but was too "advanced" an idea for the time.

Not yet commonly known, there is a class of propellant know as "Hyper-Burning-Rate" propellants which can be used for mandrels. This concept was rather loosely looked at in the 60's by way of imbedding Pyro-Core™ cord, a very fast burning lead-sheathed pyrotechnic material, in propellant grains. The results were generally unfavorable. A grain designed for very brief function at high pressure could be adapted to this mandrel method.

Unorthodox Mandrel Methods- In the early 90's we were using Asphalt as a Hybrid Fuel taking the lead of the HALO Group in Huntsville. We developed a method of extracting the simple circular rods by applying a tight spiral of Teflon™ tape. The Asphalt was cast hot, of course. We would then chill the entire assembly and then using a Tee handle, extract the mandrel by unscrewing it, the spiral tape providing a screw-thread-like configuration.

I communicated that method to a group in Tennessee. Misunderstanding the reference to tape, they used the thin plumbing variety, carefully wrapping their mandrel in one overlapping layer. They found that the metal mandrel would then easily slide out and the tape was removed by unwinding it from the core.

Paper tube mandrels were used by Hypertech in early HTPB grains. The mandrels were left in place to be burned out with the startup of the motor. Only well-glued tight tubes preferably convolute wound should be used in this method. Light-weight spiral tubes can unwind and clog a nozzle at ignition.

Creating a core shape by building it up from units has also be used extensively in the hybrid propulsion field. Applying internal fins to an acrylic tube was used by Aerocon in the early 90's for a Vandenberg AFB project. Stacking discs which have been cast or machined has been used for creating hybrid fuel grains, specifically by UTC for the FireBolt Drone motor.