International Symposium on Niobium Microalloyed Sheet Steel for Automotive Application
Edited by S. Hashimoto, S. Jansto, H. Mohrbacher, and F. Siciliano
TMS (The Minerals, Metals & Materials Society), 2006

MANUFACTURING CHALLENGES IN STAMPING AND FABRICATION OF COMPONENTS FROM ADVANCED HIGH STRENGTH STEEL

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Keywords: Steel, Joining, Welding, Forming, Springback

Abstract

Advanced high strength steels (AHSS), including dual phase, TRIP and martensitic grades, are being applied to new vehicle programs because of their contribution to efficient, mass-optimized vehicle structures. Improvements to the energy absorption, durability and structural strength of body structures result from increased usage of advanced high strength steels.

However, many manufacturing challenges must be addressed to apply these materials successfully. Forming is a unique challenge, as these materials have more formability than conventional high strength steels. Successful stamping of AHSS requires increased press force and energy. This influences selection of forming processes and die materials. Engineers must also contend with increased springback in the parts. Improvements in simulation technology are required to predict springback successfully. Simulation technology is also required to predict stress-based failures in addition to the typical strain-based failures commonly seen in stamping processes.

Joining these materials can also be challenging, as their properties depend on higher levels of alloying than is typically used in automotive body structure materials. The multiphase microstructures are sensitive to the heat input of welding processes. Higher hardenability leads to additional complexity in spot welding processes as well.

This paper will discuss these manufacturing challenges, and some of the lessons from these experiences, as AHSS become more widely used.

Introduction

Automakers continue to improve the safety, emissions and fuel economy performance of new vehicle designs. These improvements increase the requirements for vehicle structures. As a result, advanced high strength steels (AHSS), such as dual phase (DP), transformation-induced plasticity (TRIP), complex phase (CP) and martensitic (MS) are used extensively in many new programs. Numerous studies, including ULSAB-AVC [1, 2], the New Steel Body from Thyssen Krupp Stahl [3] and the Arcelor Body Concept [4], have shown that they are effective at increasing the strength and energy absorptive capabilities of vehicle structures. These features, coupled with the relatively low cost of steel for vehicle structures, are leading to great opportunities for increasing usage of AHSS [5].

Forming and joining of structures that use AHSS is challenging, and intensive development of these processes is ongoing. This paper will review several of these developments.

Typical Applications

AHSS have greater ability to absorb energy than conventional steels with the same formability [6]. This property is a result of their high work hardening capability. Thus, these steels are being used extensively in structural rail applications, where the ability to absorb higher amounts of energy in a given crush distance is valuable. Rails tend to be complex stampings, since in addition to their role in crash energy management, they are used as attachment points for other parts, and are required by packaging restrictions to take on complex shapes. TRIP and DP steels at the 600 to 800 MPa tensile strength level have the most attractive combination of strength, energy absorption and formability for rail applications. Longitudinal rails and rail reinforcements, as well as cross car beams and members are manufactured from these materials. The front rail development for the Auto/Steel Partnership Lightweight Front End Structure Project serves as an example (Figure 1) [7].

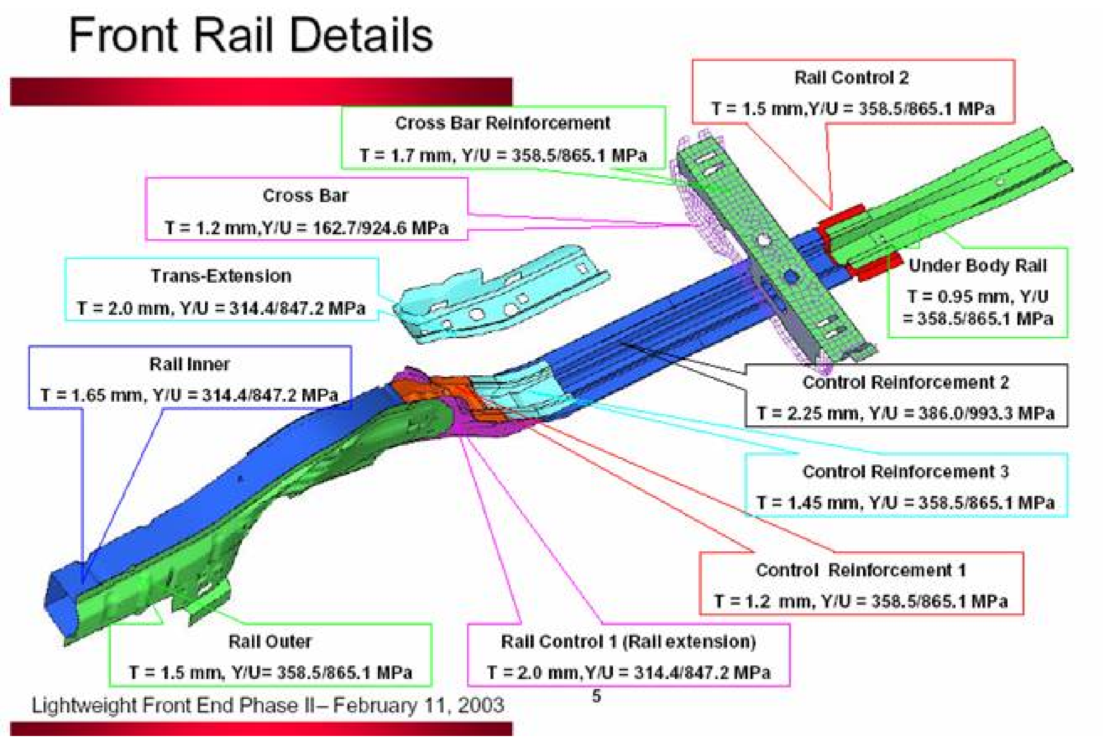

Figure 1. Front rail design from Auto Steel Partnership Lightweight Front End Structure Project – All components are Dual Phase steel. Target mechanical properties shown.

Many of the structural parts in the passenger compartment of a vehicle structure are designed to resist loads with a minimum or complete absence of deformation, in order to protect the space inside the vehicle. These applications also benefit from AHSS. As with rails, styling and packaging requirements often result in these parts being complex stampings, requiring materials with combined formability and strength capability. However, these applications have higher strength levels, resulting from higher load resistance requirements. Thus, TRIP and DP steels are used, but usually at the 800 to 1000 MPa strength levels. CP steels are also found in some of these parts at the same strength levels. Typical applications are pillars and pillar reinforcements, roof headers and bows, and other cross car beams. Rocker panels use these grades as well, if they cannot be roll formed. Door beams also utilize these materials.

MS steels meet requirements for some passenger compartment structural applications. MS materials can reach tensile strengths of 1300 MPa. However, when produced as a sheet product, the limited formability means that only parts capable of being roll formed, or stamped into simple shapes are feasible. Thus, less complicated rocker panels and reinforcements utilize MS steel sheets. Door beams and bumper beams are also typical applications for MS steels.

Hot stamping and post-form heat treatment are used to produce MS steel parts with complex shapes. These processes combine the formability of conventional high strength steel with the strength of MS steels. In hot stamping, a blank is heated above the temperature needed to form austenite, then simultaneously stamped and quenched in a water-cooled stamping die. The steel alloy has enough carbon to produce martensite at the required strength level, and enough hardenability to insure a fully martensitic structure after processing. Boron is used, in part, to provide the needed hardenability, hence these are often known as "boron steels" [8].

Parts formed at ambient temperatures from annealed steel can then be induction heat treated after forming to the required strength level [9]. An advantage to this process is that the part can have different mechanical properties in different areas of the part. However, these processes must be developed carefully, as the non-uniform heating can result in dimensional changes in the final part.

Forming Challenges

The strength of AHSS materials results in high stresses in the materials during the forming processes and high force requirements for stamping equipment, compared to conventional steels. The high stresses result in high levels of springback, twist and curl when the parts are released from the tooling. The high force requirements in the stamping equipment must be considered in the selection of stamping presses and in the selection of tooling materials and lubricants.

Dimensional control of AHSS stamped parts has been a major challenge to this point, and the focus of much development work. The development of processes resulting in dimensionally acceptable parts requires extra time, which adds cost, and in extreme cases can delay introduction of new vehicles. In some cases, redesign is the only alternative. The efforts to overcome dimensional control issues are focused in two areas: process simulation/die face compensation, and stamping process development to minimize springback.

Simulation Development

Finite element analysis of stamping processes has long been used to develop die faces and binder surfaces that result in formable parts with acceptable springback. The accuracy of these simulations in mild steel is quite good. Recent studies have shown that finite element methods accurately predict formability of AHSS as well [10]. However, springback simulation results are less accurate. The higher strength levels in AHSS materials lead to higher levels of springback, and the simulation tools are not as well developed.

The high level of work hardening in these materials requires accurate modeling of yield surfaces and work hardening behavior for accurate simulation of final dimensions. Researchers are working on improved hardening models, as well as considering the Bauschinger effect, in order to improve the predictions [11, 12]. Recent results have been encouraging, however the materials testing needs to support these simulations may go beyond simple tensile testing, to incorporate shear testing and multiaxial deformation testing [13].

Effective finite element modeling requires a balance between the mesh requirements for proper evaluation of a problem, and the computational resources needed to do the analysis quickly and economically. Modeling of springback in AHSS parts increases the computational requirements by requiring higher levels of accuracy in stress predictions. This can result in a need for finer meshes [14], which increases time and cost of analysis.

The ultimate goal for simulation of part shape after stamping is to provide capability for a "virtual" die tryout, leading to die faces altered from the part shape in order to compensate for springback. Done successfully, it would eliminate the need for additional tryout time for AHSS parts [15]. An interim step is to use finite element analysis to develop die face compensation based on the results from an initial tryout of the actual tool, with the die face cut to the part shape [16]. This strategy does not eliminate the need for additional tryout for AHSS materials, but does reduce it.

As mentioned previously, the capability for finite element analysis to predict formability of conventional steel parts is well established and quite accurate. One reason for this accuracy is that forming splits are predictable from strain-based criteria. Keeler showed that even for high strength materials up to 550 MPa yield strength, forming splits are quite predictable from strain-based criteria [17], and this behavior has been demonstrated for AHSS materials as well [18, 19]. However, AHSS materials with tensile strengths above 800 MPa can exhibit ductile shear fracture on bend radii, under tensile loads, an unusual failure mechanism in sheet metal (Figure 2). The ability of finite element codes to predict this failure has not yet been established. Fractures of this nature occur when a critical stress is exceeded. Improved stress calculating capability will be required for robust split/fracture prediction, as well as robust springback prediction.

Figure 2. DP800 stamping exhibiting shear fracture.

Processing

Process developments to minimize springback and maximize part quality revolve around controlling metal flow. The effectiveness of stretching the walls of stamped parts to minimize or eliminate springback is well established [20]. This strategy works for AHSS materials, however their high strength makes it more difficult to execute. Appropriately designed structural parts can be processed with two- or three-piece form dies. A lock step in the lower post is effective at stretching the walls of these parts when conventional steels are used (Figure 3). However, a simple two-break lock step, as shown in this figure, does not supply sufficient restraining force to stretch walls in AHSS. A four-break lock step is effective in reducing springback and curl in a relatively shallow part. However, this process only works for relatively simple parts with minimal compression in sidewalls or flanges. The stretching effect can be augmented if necessary by adding a lower pad to the tool (Figure 4).

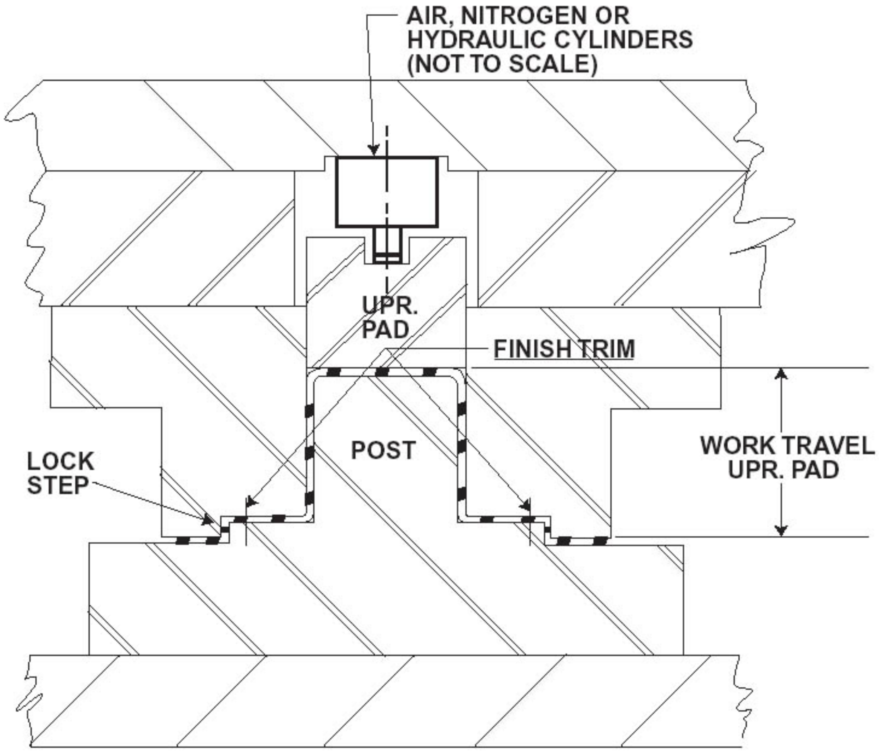

Figure 3. Post stretch form die - showing lock step which helps stretch sidewalls (from Auto/Steel Partnership High Strength Steel Design Manual) [21].

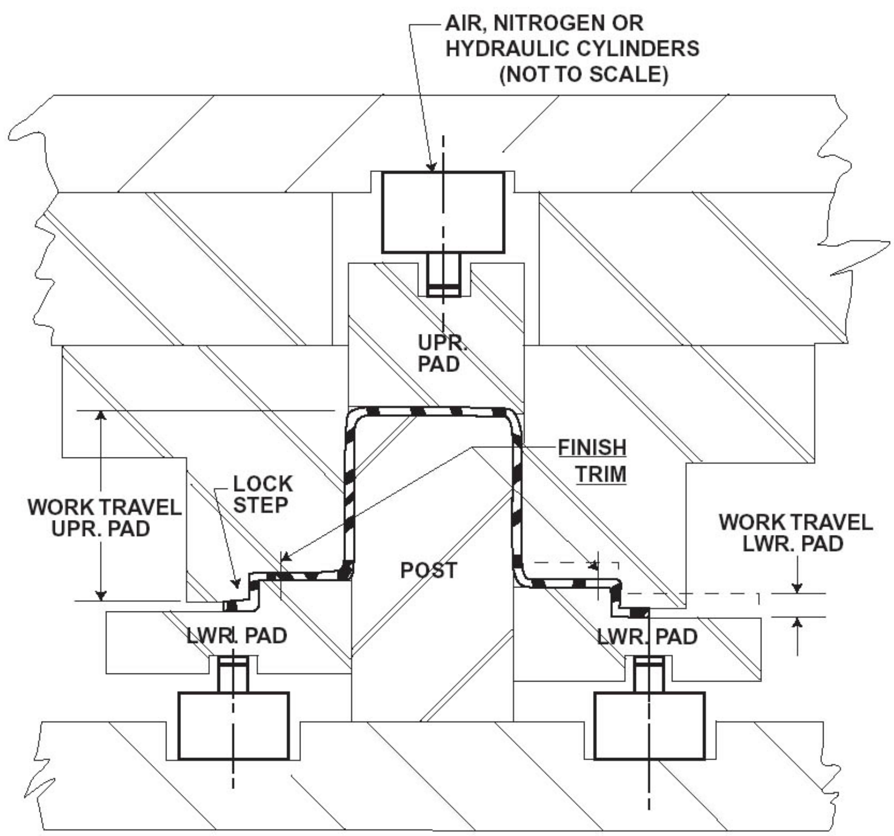

Figure 4. Post stretch form die with lower pad to enhance sidewall stretch (from Auto/Steel Partnership High Strength Steel Design Manual) [21].

Parts that are more complicated require a draw die with an active binder, to control wrinkling in areas of metal compression (Figure 5). These types of tools are especially problematic for AHSS parts, because the force requirements to keep the binder closed are quite high. Severe wrinkling must be eliminated through blank development or part shape changes, since conventional levels of binder force are not an effective means of controlling wrinkling in AHSS processes. Additionally, this process usually results in high levels of sidewall curl, caused by non-uniform deformation resulting from material being drawn off the binder and over the punch radius. It is difficult to develop sidewall stretch in this process. In order to stretch the sidewalls, an additional increment of restraining force must be developed near the bottom of the stroke. This can be done with a pressure system (in either the press, or the tool) with variable force capability through the stroke. The system must be programmed to deliver an increase in binder force near the bottom of the stroke, balancing the restraining force required to pull out the springback and curl with forming limits of the part. The high force requirements mean that this system is likely to be hydraulic, rather than pneumatic. An active draw or lock bead, which can be mechanically timed to engage at the appropriate time near the bottom of the stroke, can accomplish the same effect [22]. In summary, the development of AHSS parts that require active binders is quite difficult, and should be avoided in favor of two- or three-piece form die processes. Obviously, part complexity requirements will not always allow this, so development of processes with active binders will continue.

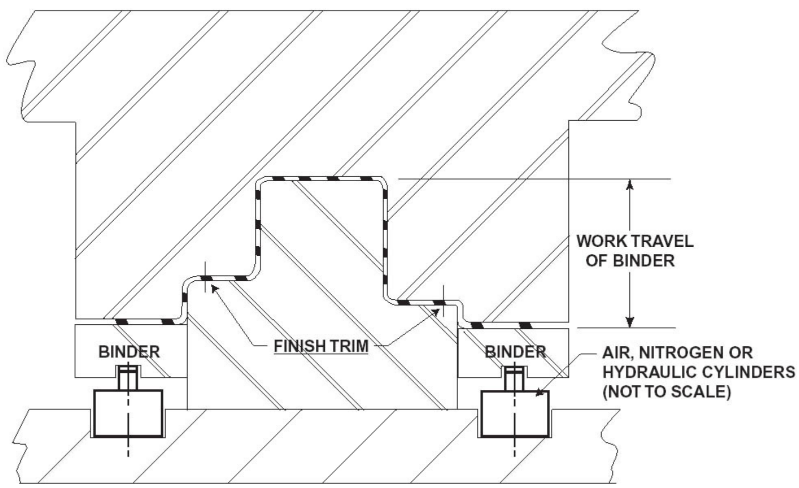

Figure 5. Draw die in single action press. An upper pad (not shown) is often used to control part shape (from Auto/Steel Partnership High Strength Steel Design Manual) [21].

In processes with active binders, the increased forming loads generated by AHSS compared to conventional high strength steels are modest in comparison to the increase in binder force requirements. For parts with deeper draw depths, and hydraulic binder force systems (which develop maximum force shortly after binder contact), evaluation of compatibility with proposed press systems is important. The high forces that can be encountered high in the press stroke risk overloading presses that might otherwise be appropriate for forming the part.

The high strengths of AHSS parts can result in high temperatures and extreme wear conditions in the tooling. The high temperatures are a result of the energy absorbed during forming caused by the high work hardening characteristics of the materials. It is important to note that frictional heating is not the cause of the high temperatures, and additional lubrication will not help reduce the tooling temperature unless large quantities to quench the system. The combination of high temperature and high stresses has resulted in the application of high performance coatings, and even ceramic inserts, for AHSS stamping tooling [23, 24].

Joining Challenges

The high-strength-low-alloy (HSLA) steels are, by design, highly weldable materials. The base microstructure of HSLA steel is soft, stable ferrite. Strengthening results from precipitation hardening and grain size effects, and the hardenability of these materials is not significantly higher than mild steel. Resistance spot welding and metal-inert-gas (MIG) welding of HSLA steels is common in vehicle manufacturing, and the processes are quite robust.

AHSS materials contain significant fractions of hardenability-enhancing elements, such as carbon, manganese, silicon, molybdenum and chromium. These are necessary to produce the volume fractions of martensite and bainite needed to provide the high strength and high work hardening characteristics of the materials. The enhanced hardenability does not affect the ability of the material to form an acceptable resistance spot weld. However, it does increase the propensity of the weld metal to be harder than the base metal and for the weld nugget to fail (rather than the base metal) when the weld is pulled apart. This leads to difficulty in weld quality control, since a good weld that fails in the nugget can be visually similar to an inadequately formed weld, even though it has adequate strength. Since destructive weld testing is a key component of quality control of weld processes in vehicle manufacturing, the welding parameters, including the metal stackups, weld currents and dwell times, will be limited to insure that current quality control processes remain valid. Metal stackups that include mild or HSLA steels are more robust, since their presence dilutes the alloy level in the weld pool. Dwell times after the current pulse must be limited, to maintain heat in the weld, allowing time for self-tempering. Non-destructive evaluation is being developed to bring more robust quality control processes to the production line, resulting in more accurate quality assurance practices.

MIG welding appears to be a feasible process for joining of AHSS materials [25], but the applications are so new that industry standards for this practice are still being developed. Laser welding is also feasible; tailored blanks made from AHSS materials have been shown to be sufficiently formable for commercial application [26, 27]. Weld bonding is another joining technique that is compatible with AHSS materials. It is being intensively developed but is only just now being seen in commercial practice.

Summary

AHSS materials offer attractive combinations of strength and formability, which make them uniquely suited to meet the increasing demands on vehicle structures. Forming and joining processes are being intensely developed. Many parts are already in volume production and more are joining them every day. Even so, one cannot conclude that the challenges associated with the forming and joining have been adequately resolved. More work remains to be done.

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