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Automotive Application and Forming Problems for New Sheet Materials*

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Synopsis:

The overall obstacles to lightweight sheet metals application in vehicles are briefly reviewed in this paper with particular emphasis on sheet metal forming problems. Results of a survey indicate that sheet forming is the largest barrier to further high strength steel application; however, for sheet aluminum, cost and welding difficulties are as significant obstacles as the important sheet forming problems. Reduced stretchability and sharp radii sensitivity for both classes of materials are the major limitations and these cause a wide variety of independent failure modes in sheet forming.

The overall advantages of the application of these materials are very briefly reviewed. Four areas of progress towards overcoming the forming problems are discussed: (1) materials characterization, (2) improved procedures and guidelines, (3) new forming processes or approaches, and (4) improved materials. Progress in all areas has been highly useful in achieving increased application of the new lightweight sheet metals and the continued importance of new approaches (or processes) to sheet forming is highly likely. Such progress will be essential to the continued realization of the significant benefit of lightweight sheet metal utilization in vehicles: cost-effective decreases in fuel consumption.

I. Introduction

This paper is concerned with materials for weight reduction in private transportation vehicles. There is a considerable history of achieving weight reduction in automobiles by material substitution as vehicle weight has always been an automotive design criterion. The application of heat treated higher strength steels in suspension components for weight saving (and space saving) dates to the earliest days of chassis development. Indeed, use of such steels was a key ingredient in the advances made in the original Model T. Automotive usage of aluminum dates from the 1920's, whereas plastics in vehicles for weight reduction is a more recent phenomena. The present paper discusses the intense activity in lightweight sheet metal for the last decade. The beginning of the new drive for weight reduction[1)2)] resulted from the weight increases due to increasing size, power requirements and by emission and safety standards. All of these factors converged with rising energy prices (fuel economy increases desired) to make U. S. interest in weight reduction particularly intense in the last five years.

This paper covers two categories of lightweight materials: high strength sheet steels (HSS) and sheet aluminum products. The chief fabrication processes involved with manufacturing vehicles from these materials are sheet stamping and spot welding. The major distinguishing characteristic of the activity since 1970 (relative to earlier HSS) has been its focus on decreasing the weight of *stamped* and spot welded structures. Our knowledge of these fabrication processes has had to expand to new *material classes* being developed and supplied for weight reduction.

Table 1 summarizes for HSS some of the key technological dates. The earliest applications were in 1972 and there has been consistent progress applying these materials in new components into the current period. Some of the key developments in HSS were: (1) the development of cold

Table 1. Highlights of high strength steel sheet application to U.S. vehicles.

1969	Hot rolled, controlled-cooled HSLA developed
1972	Application to engine mounts
1973	Inclusion shape controlled materials introduced
1974	Bumper reinforcements (50 ksi)
	Side-door beams
1975	Cold rolled high strength sheet steels developed
1976	Bumper facebars (50 ksi)
	Side-door beams (140 ksi-roll formed)
	Exterior panels (40 ksi)
1978	Application to body structural parts (40 ksi)
	Wheels, suspension arms (80ksi)
	Frame members (50ksi)
	Dual-phase steels emerge
1979	Coated cold rolled high strength steel
1980	Redesigned structural applications (80ksi)
1984-8	Vehicle wide optimal application (60 to 140 ksi)

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Table 2. Highlights of modern sheet aluminum application to U.S. vehicles.

1971	AU2G introduced in France
1972	2036 introduced
1973	2036 applied to load floor
	5182 hood inner
	6061 extruded bumper reinforcements
1974	7016 bright anodized bumpers
1976	6009/6010 introduced
1977	7029 bumpers
	2036 outer hoods and decklids
	air cleaners, heat shields, fuel filler pipes
1978	6009/6010 truck bodies
1979	Stamped aluminum wheel, seats
1981	2038 introduced
	Stamped suspension components
1984-9	Structural body parts?
	High aluminum content vehicles?

rolled high strength steels, (2) the improvement of formability in the materials–particularly the evolution of dual phase steels– and (3) the wider availability of high strength and coated products. The remaining challenge is yet very difficult as it will involve the optimal achievement of weight reduction by application of the high strength materials throughout the vehicle.

Table 2 shows some key technological dates for the modern efforts in sheet aluminum alloys. The development of materials with some improvement in spot welding (the AU2G and 2036 alloys) marked the beginning of modern sheet aluminum application. In this evolution, we also note the general spread of the various materials into different components of the vehicle. The application of these materials thus far has been much more limited in volume than HSS and indeed, the achievement of high volume aluminum sheet application has been retarded by competition with the high strength sheet steels. The key problem involves developing sheet aluminum applications whose weight reduction is significant enough to warrant the attendant cost penalty[3].

The problems concerned with these evolving sheet metal technologies are many, particularly if we consider the varieties of materials and applications that are involved. In Section II, I will first consider the overall obstacles to application of each class of material and then specifically discuss problems in the forming area in more detail. In Section III, I will review some of the progress that has been made in overcoming the forming obstacles before considering the advantages and overall progress in Section IV. It should be noted at the outset that all of the applications of the new materials have required some adaptation either in the design, manufacture or in the materials themselves. These adaptations or solutions can sometimes themselves introduce additional problems and so may offer less than satisfactory solutions.

II. Obstacles to Sheet Aluminum and HSS Applications

A. Overall Problems

Much has been said and written about problems that can and have been encountered with automotive application of these materials. Different experts give different assessments of their relative importance. Thus, to obtain a broader view of U. S. experience, a questionnaire was distributed at the April, 1981 ADDRG meeting. Some findings are shown in Appendix I in the general form of the original questionnaire. The numbers in the personal information section show the distribution of people responding (82 total) and the numbers in the ranking columns (Questions 1–5) average the answers for each question. The numbers in parentheses behind each ranking show the number of respondents to each item.

The perceived restraints to application for each class of materials were addressed in question 1. For the high strength sheet steels, the chief obstacle is forming since it polled the highest average severity ranking. In addition, reproducibility, overall manufacturing knowledge, overall design knowledge, and dissemination of knowledge also are seen as important roadblocks. The obstacles for application of sheet aluminum were similarly perceived– as listed in the aluminum column in question 1. Perhaps not surprisingly, however, cost and welding of sheet aluminum emerge as even more significant obstacles than forming.

B. Forming Problems

Questions 4 and 5 in the survey pursued the formability aspects further. Question 5 addressed the failure modes and forming process problems important for the sheet metals. For high strength steels, production experience indicates an important range of failure modes. In particular, edge cracking, fracture during hole expansion, stretch failures, excessive springback and wrinkling predominate as failure modes. One of the most important findings of the survey is the wide variety of somewhat independent difficulties that arise with forming these higher strength, less ductile materials.

For sheet aluminum, production experience indicates the prevalence of most of the problems that are found for the high strength sheet steels (with the exception of difficulty in hole expansion possibly because certain parts have not been tried). In addition, excessive galling and choice of lubricant are also cited as processing constraints in the application of sheet aluminum. Again, it can be noted that the forming problems involve a variety of independent failure modes.

The forming problems were addressed in question 4 from the point of view of material properties. Properties which caused the most dificuly in application of these materials were judged to be lack of stretchability, and sharp radii sensitivity for both classes of materials. Other ranking of material properties were similar for the two classes of materials with the anticipated difference due to the decreased rate sensitivity of sheet aluminum.

The combination of ranking emerging from these two questions and experience in the application of these materials make it clear that the reduced elongation and/or higher strength introduce a variety of significant forming problems. In the following section, therefore, I will briefly discuss some of the progress that has been made in addressing these problems.

III. Progress in Forming Lightweight Sheet Metal

In view of the complexity of metal forming and the wide variety of new materials, it is not surprising that progress has been relatively slow. Nonetheless, our ability to successfully form parts from these materials has increased significantly over the past decade. The advances have resulted from experience and development in a number of areas; thus, we will discuss four of the significant areas in this section.

A. Materials Characterization

In the early stages of application of these new sheet materials, little was known about their forming characteristics, aside from tensile properties. Information about most of the materials is still incomplete; moreover, there is not general agreement on what kinds of information are most essential. However, many of the materials have now been characterized by forming limit diagrams, limiting dome height measurements, bend radii measurement and a variety of other experimental techniques. I will not attempt in this paper to review the variety of material measurements that have been made, but instead, summarize some significant recent results.

In many stretch-forming measurements (see figure 1), there is not a great difference among the various sheet aluminum alloys being applied. On the other hand (figures 2 and 3), there are significant differences among the varieties of high strength steels being evaluated (particularly if we consider the low ductility recovery annealed steels). This is in large part due to the much greater range of strength being utilized within the class of high strength sheet steels. Thus, much care must be exercised when attempting to discuss HSS as a class of materials.

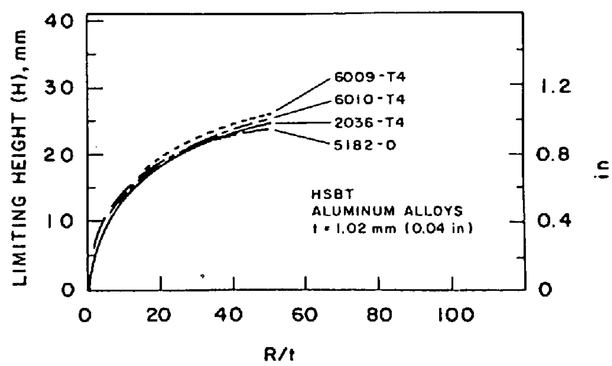

Fig. 1. Limiting stretch heights in hemispherical domes for a variety of aluminum sheet alloys from DEMERI[4].

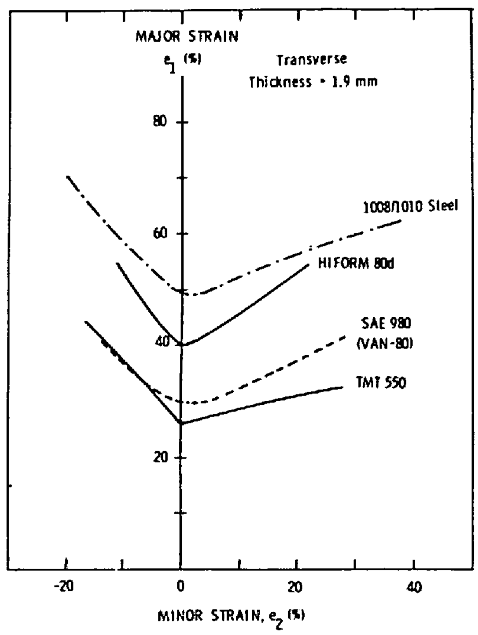

Fig. 2. Forming limit diagrams for several high strength steels from BRAZIER and STEPHENSON[5].

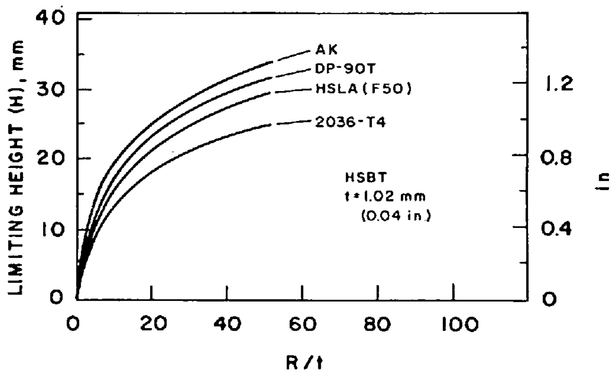

Fig. 3. Limiting stretch heights in hemispherical domes for various HSS sheet[4].

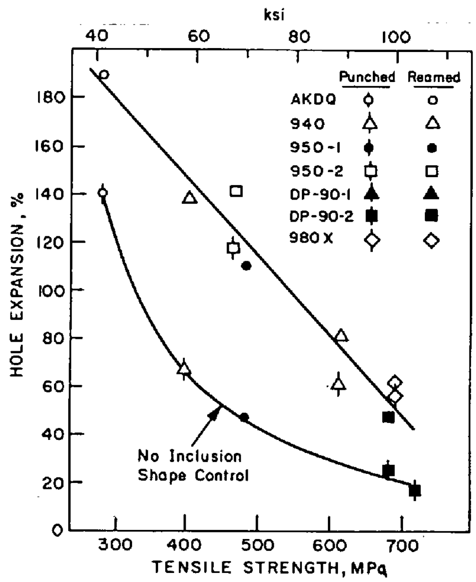

Fig. 4. Hole expansion percentages as a function of material strength for a variety of HSS sheet Davies[6].

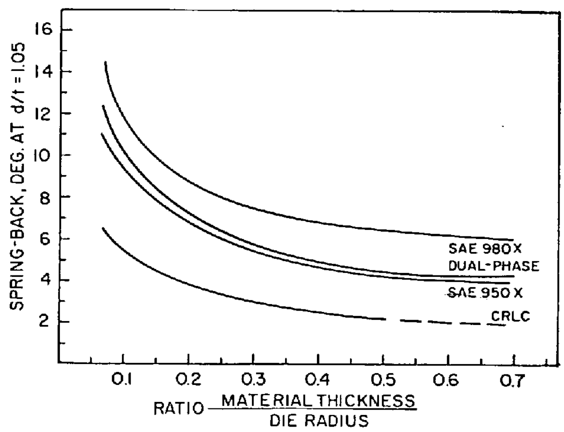

Fig. 5. Comparison of springback for several HSS sheet materials at a die gap to material thickness of 1.05 as a function of material thickness to die radius after Davies.

Recent measurements of the forming limits in complex forming operations have provided information such as those shown in figures 1 and 3 from Demeri's work[4]. In addition, measurements of edge cracking sensitivity has now been performed on a wider number of high strength steels by Davies[6], figure 4. Inclusion shape control and strength level have significant influence on hole expansion capability. Measurements of springback for a wide variety of HSS have also been reported by Davies[7] and some results are given in figure 5.

The importance of an improved level of knowledge of material formability cannot be overemphasized. As more experimental results become available and as recognition of the independent failure modes grows, it has become possible to rationally utilize such data in practical metal forming. Indeed, such measurements have formed an important basis for developing guidelines for the forming of these materials.

B. Forming Guidelines and Improved Procedures

A variety of lessons that have been learned from die trials have been reduced to initial guidelines. For both sheet aluminum[8)9)] and high strength sheet steels[10] there are now simplified guidelines on die radii, wall angles, extruded hole height, bend radii, and other forming parameters. In addition, there have been attempts to reduce simple material property measurements (as reviewed in Subsection A above) into simplified design guidelines. These guidelines are proving to be extremely useful in the orderly application of the high strength sheet metals and the efforts to systematize the body of information is moving ahead.

In addition to the evolution of new experience-based guidelines, there has been a simultaneous development of new methods for forming and die design. Significantly, the introduction of computer-aided die design and the application of computer graphics to the process of binder development has occurred simultaneously with the evolution of the new sheet materials[11]. In many cases, these new techniques have made possible the introduction of the lightweight sheet metal technology in a more productive fashion. The ability to geometrically visualize the interaction of material, die and punch has been an important asset in the more rapid assimilation of experience to later production. Ongoing research and new analytical procedures for understanding the sheet forming process also have been of help in the application of the high strength sheet metals. Nonetheless, the wide variety of materials and the wide variety of failure modes that do occur (without a complete physical explanation) mean that the evolution of die design guidelines that are not overly conservative continues to be a slow process.

C. New Forming Processes and Approaches

Many approaches to avoid forming difficulties introduce cost penalties since they sometimes necessitate larger blanks or more generous radii which can add useless material or limit design options. Thus, new process approaches that can be adapted specifically to the inferior properties of these materials can provide more cost-effective solutions. There has been some progress along these lines in the past ten years and a few cases can be discussed further.

An example of a new forming process that has achieved some widespread success in the application of low elongation materials is the roll forming process. This process now is being applied to numerous side door beams in U. S. cars[12] and to some bumpers as well. Roll forming does not involve significant stretching or excessive wrinkling and so offers a natural solution for materials with low tensile elongation.

Hemming of outer sheet panels is often the most effective joining process but strain localization in aluminum has caused problems in practice. A method for gradually introducing the hem and avoiding cracking is shown in figure 6[9].

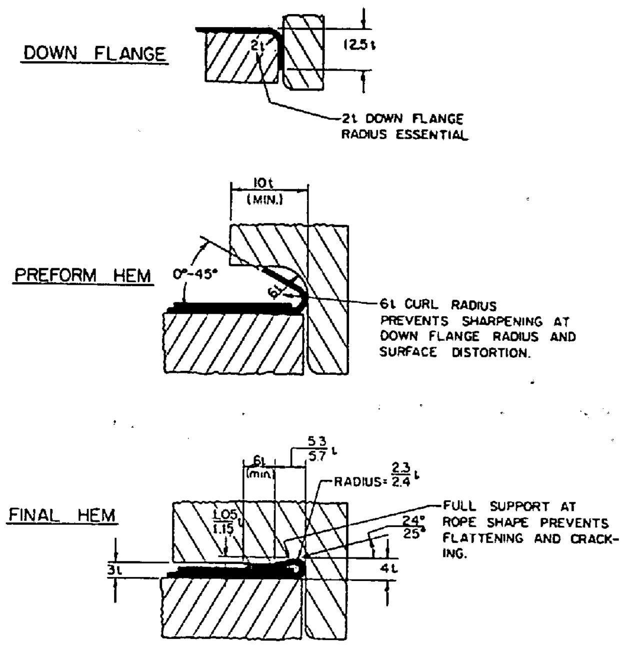

Fig. 6. New rope hem tool design[9].

Draw-forming of larger outer panels involves a complex technology that has evolved around the properties of mild steel and is particularly sensitive to reduced material properties. Forming these panels with outstanding surface quality by avoiding wrinkles and loose metal is more difficult than is generally understood. Analysis by DUNCAN and BIRD[14] of the conventional process for forming these panels indicates the severe difficulties of forming acceptable panels in materials having reduced yield to tensile strength ratio. This is an area in which new processes and new approaches may be needed; "stretch-forming" represents one such new process. One variation, shown in figure 7, involves turning the normal forming process upside down so that the binder pulls the sheet down over the punch. The process makes it easier to avoid wrinkling and to get adequate stretch across a panel in a material which cannot be stretched to large strains. The technique should be applicable to high

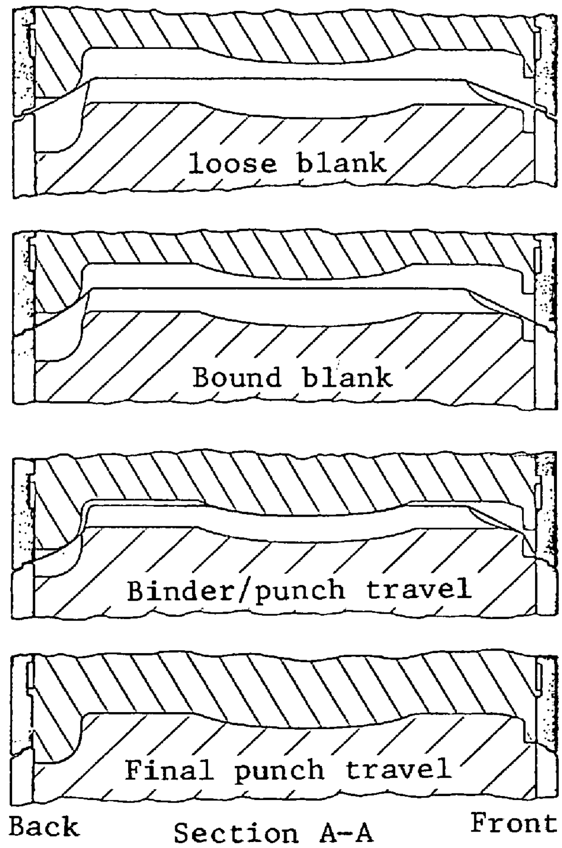

Fig. 7. Stretch stamping process after Wolff[13].

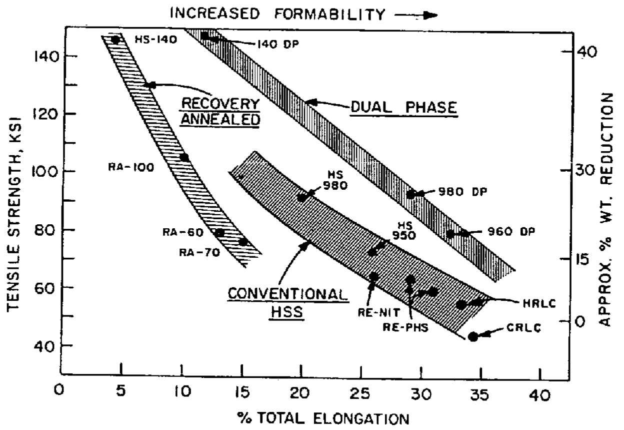

Fig. 8. Tensile strength as a function of elongation for the wide variety of available HSS sheet demonstrating weight-reduction/formability tradeoff[17].

strength sheet steels and sheet aluminum materials as well as to mild steel. In the case of mild steel, the added tolerance of this process is not necessary, but in the new less ductile materials it may well be.

D. Improved Materials

An important element of progress throughout the application of these new sheet materials has been the evolution of new materials. Tables 1 and 2 show some of the important materials that have evolved during this period.

In high strength sheet steels, important developments have been the commercial availability of cold rolled high strength steel and coated high strength steels. However, the major breakthrough in new material properties have occurred in the cold rolled and continuously annealed products first developed in Japan[15][16]. The dual phase steels show the possibility for significant increases in forming at any given tensile strength (figure 8). In applications where tensile strength is the proper design property, formability can be significantly increased at a given weight reduction. It is perhaps significant that the survey results shown in Appendix I (question 2) do indicate strong expectations that these materials will be more important in the future.

A second aspect of continuously annealed materials that may well be as important in overcoming forming problems is the increased reproducibility expected with these materials. Appendix I, question 1, indicates the emphasis–particularly for high strength sheet steel–placed on material reproducibility. Manufacturing personnel particularly have been concerned with this problem.

Major developments in aluminum have involved alloys which are capable of bright anodizing, and alloys with improved spot welding and recyclability. Improved formability of sheet alloys would be enhanced by increased resistance to edge cracking and/or capability of stretch forming. Any significant development along these lines would have an important influence on the future application of either class of materials.

IV. Advantages of Lightweight Materials Applications

Obviously other factors in addition to formability difficulties can limit the application of the lightweight sheet metals. For each class of materials, significant reviews of these factors have been published[9][16][17]. Thus, the discussion will be limited to the applications and citation of some very recent work in special areas.

For each class of material, the key design problem has been to determine the degree of weight reduction possible with the various materials in all the different applications possible in vehicles. Complete answers to this question clearly is not in sight but improved knowledge has been constantly emerging. Figure 9 shows the expected weight reductions for high strength sheet steels in energy absorption applications. Similar information exists for durability of HSS and for sheet aluminum in energy absorption and durability[19] applications.

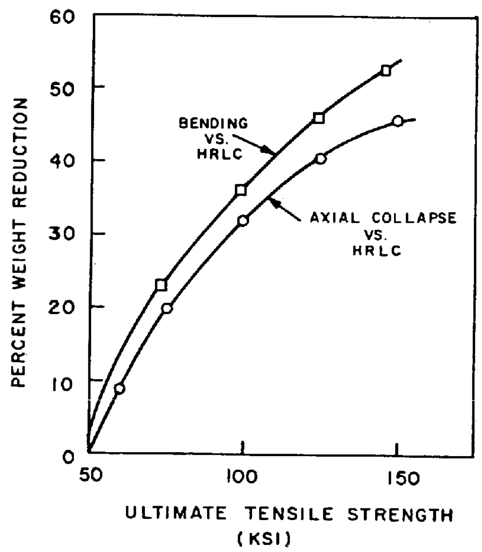

Fig. 9. The degree of possible weight reduction as a function of tensile strength for HSS sheet.

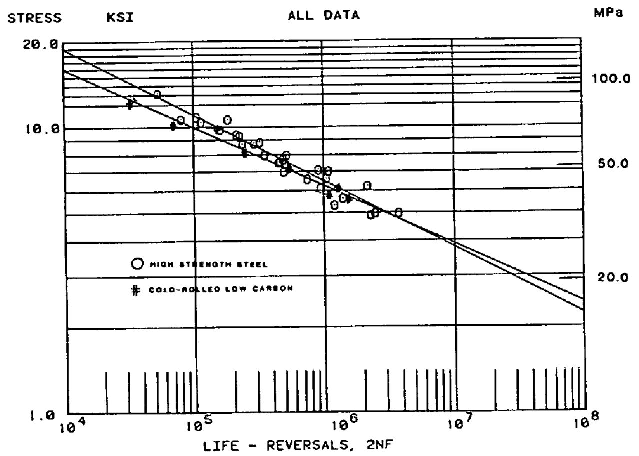

Fig. 10. Fatigue life of a variety of HSS and mild steel spot-welded sheets in tensile shear after KRAUSE[22].

The application of results such as those shown in figure 9 to actual vehicle structures is not simple, however. One of the key areas that remains under investigation is to understand the effect of spot welds on the behavior of these materials when used in vehicle structures. Recent work on the energy absorption of spot welded high strength steel tubes indicates some reduction in the degree of weight savings possible in spot welded structures as compared to unwelded structures[20].

Such results have not been reported for the case of sheet aluminum but earlier results[21] would suggest that the possible weight reduction may be even more diminished than for HSS.

For the durability of spot welded structures, past results indicated (in certain loading modes) a similarity in fatigue endurance of high strength and mild steel spot welds. Recent work in this area by KRAUSE[22] has led to the results shown in figure 10. These results indicate that for a given amount of downgaging the same area of spot weld is needed independent of the type of steel sheet.

Other important areas not covered in the survey given in Appendix I involve the quality control and non-destructive evaluation of products made from these new materials. There has been some progress attendant with the new forming tests to control the properties of incoming material. However, it is clear that the entire evolution of materials specifications and quality control of these materials is still in the early stages.

V. Concluding Remarks

The weight reduction possible with these new sheet materials in the overall vehicle are significant. In the case of high strength sheet steels, extensive application of high strength materials throughout the vehicle might lead to vehicle weight reductions approaching 10%. This could lead to significant fuel consumption reductions[3] and if the fabrication cost penalty can be kept minimal, significant amounts of fuel can be saved at relatively low total cost. Thus, continued progress and evolution towards better understanding and capability of handling these high strength sheet materials in the manufacturing environment is of great value. For both HSS and aluminum, it is also imperative that we continue to find applications in which the optimal weight reductions are achievable. This is particularly important in the case of aluminum because otherwise, the weight savings may not be worth the cost penalty in terms of the fuel that they save[3]. It is also clear that the major roadblocks to future HSS application involve sheet metal forming where new approaches may offer some of the largest future gains.

Acknowledgements

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References

1) *K. O.* MARSHALL: "The Economics of Automotive Weight Reduction", SAE Paper No. 700194 (1970)
2) *L.* ARTINIAN and *S. L.* TERRY: "The Total Cost of Weight", SAE Paper No. 325D (1961)
3) *C. L.* MAGEE: "The Role of Weight Reducing Materials in Automotive Fuel Savings", to be published in SAE, Ford Motor Company Technical Report (1981)
4) *M. Y.* DEMERI: "The Stretch-Bend Forming of Sheet Metal", to be published in J. of Metalworking, (1981)
5) *W. G.* BRAZIER and *R.* STEVENSON: "Evaluation of a New Dual Phase, Cold Rolled Steel-Formability", SAE Paper No. 780137 (1978)
6) *R. G.* DAVIES: to be published.
7) *R. G.* DAVIES: "Springback in High Strength Steels", to be published in J. of Metalworking (1981)
8) *N. P.* WOLFF: "Interrelationship Between Part

and Die Design for Aluminum Auto Body Panels", SAE Paper No. 780392 (1978)
9) *N. W.* SMITH and *J. E.* GRANT: "Reducing the Cost of Aluminum Body Panels", SAE Paper No. 800931 (1980)
10) National Steel Automotive Technical Bulletin, "Forming FO-2A9" (1978)
11) *H. O.* MCCORMICK: "CAD/CAM for Automotive Die Design", Society of Manufacturing Engineers, No. NS 77-768 (1977)
12) *T. E.* FINE and *S.* DINDA: "Ultra-High Strength Roll-Formed Door Beams", SAE Paper No. 750220 (1975)
13) *N. P.* WOLFF: "Part and Die Design for Forming Automotive Sheet", Automotive Aluminum Design and Fabrication Seminar, The Aluminum Association, November (1980)
14) *J. L.* DUNCAN and *J. E.* BIRD: "Die Forming Approximations for Aluminum Sheet", Sheet Metal Industries (1978) p. 1015
15) *S.* HOYAMI and *T.* FURAKAWA: Proc. Microalloying Conference, Washington, D. C., (1975) p. 78
16) *C. L.* MAGEE and *R. G.* DAVIES: "Automotive Sheet Steels for the 1980's", Alloys for the 80's, Climax Molybdenum Co., (1981), p. 25
17) *C. L.* MAGEE, *R. G.* DAVIES, and *P.* BEARDMORE: "Factors Influencing Automotive Applications of High Strength Steels", J. Metals, 32, (1980) 11, p. 28
18) *C. L.* MAGEE and *P. H.* THORNTON: "Design Considerations in Energy Absorption by Structural Collapse", SAE Paper No. 780434, SAE Transactions (1979)
19) *A. M.* SHERMAN, *R. G.* DAVIES, and *A. R.* KRAUSE: "Fatigue Life Predictions for High Strength Steels in Automotive Applications", SAE Paper No. 810435 (1981)
20) *P. H.* THORNTON: "Energy Absorption by the Structural Collapse of Spot-Welded Sheet Metal Sections", SAE Paper No. 800372 (1980)
21) *K. F.* GLASER and *G. E.* JOHNSON: "Construction Experience on Aluminum Experimental Body", SAE Paper No. 740075 (1974)
22) *A. R.* KRAUSE: "Fatigue of Spot-Welded Steel Sheets", to be published (1981)

APPENDIX I

LIGHTWEIGHT MATERIALS SURVEY

Personal Information — Check as Appropriate

Type of Company/Division/ Institution	USER	36 Automotive 8 Non-Automotive	SUPPLIER	22 Steel 7 Aluminum	OTHER 14
Job Function:		59 Research 16 Manufacturing		8 Product Engineering 10 Other	

QUESTIONS

Answer Code:

0 = no opinion or do not know
1 = no significance
2 = little significance
3 = moderate significance
4 = very important
5 = among the most important
i.e. extremely significant

PLEASE TRY TO ANSWER ALL AREAS, BUT IF YOU FEEL YOUR BACKGROUND IS NOT APPROPRIATE, USE ZEROS (0) LIBERALLY

1. What are the major roadblocks to further vehicle applications?

	High Strength Sheet Steels	Wrought Aluminum
Cost	2.7 (66)	4.2 (62)
Forming	3.9 (73)	3.8 (63)
Welding	2.8 (63)	3.9 (55)
Availability	2.4 (66)	2.5 (56)
Finishing/Corrosion	2.9 (56)	2.5 (53)
Reproducibility	3.5 (64)	3.0 (51)
Complexity	3.0 (48)	3.1 (36)
Overall Manufacturing Knowledge	3.4 (60)	3.6 (52)
Rigidity	2.6 (56)	3.3 (55)
Crash	2.4 (56)	3.2 (50)
Denting	2.4 (59)	3.3 (55)
Durability	2.5 (54)	2.8 (52)
Overall Design Knowledge	3.6 (57)	3.6 (51)
Dissemination of Knowledge	3.3 (58)	3.3 (49)
Other ____________	2.7 (03)	2.7 (03)

↑ ↑
(Average Response) (No. of Respondents)

This questionnaire appeared with blanks and was given to 82 people (distributed as shown in Personal Information Section). The average response and number of non-zero responders is shown with each question.

2. In your opinion/judgement, which of the materials classes are most important (rank relative importance within each grouping not considering other materials)? (5 is most important)

High Strength Steels

		Now	Future
Conventional HSLA	945 and below	3.7 (55)	3.1 (49)
	945 to 965	3.8 (55)	3.8 (49)
	965 and above	2.9 (54)	3.2 (50)
	Dual-Phase	2.4 (53)	3.5 (54)
	Recovery Annealed	2.5 (53)	2.3 (49)

Wrought Aluminum

	Now	Future
2000 series	3.2 (24)	3.0 (23)
5000 series	2.9 (22)	2.8 (21)
6000 series	3.0 (24)	3.3 (23)
7000 series	2.9 (23)	2.8 (22)

3. What application areas are most significant for application of the lightweight materials? (5 is most significant)

	High Strength Steels		Wrought Aluminum	
	Now	Future	Now	Future
Outer Panels	2.8 (62)	3.4 (54)	3.4 (39)	3.7 (32)
Body Structure	3.7 (61)	4.1 (54)	1.9 (31)	2.8 (31)
Chassis Structure	3.9 (56)	4.3 (50)	1.9 (30)	2.7 (30)
Bumpers	3.9 (59)	3.9 (52)	3.7 (38)	3.4 (33)
Interior Components	2.2 (47)	2.4 (44)	2.8 (34)	3.0 (28)
Other ______	-	-	-	-

4. As a whole, what are the major material properties that limit forming for each overall class of materials? (most important properties for limits = 5)

	High Strength Steels	Wrought Aluminum
Drawability	3.4 (62)	3.7 (40)
Stretchability	4.0 (64)	4.1 (43)
Sharp Radii Sensitivity	3.9 (60)	4.1 (41)
Elongation	3.7 (63)	3.5 (41)
High Strength *per se*	3.0 (50)	2.7 (31)
Fracture Toughness	2.8 (44)	2.8 (27)
Reduction in Area	2.9 (50)	2.9 (28)
Work Hardening Rate	3.4 (58)	3.3 (36)
Rate Sensitivity	2.9 (49)	3.4 (35)
Reproducibility	3.8 (55)	2.9 (33)
Other ______	___ (03)	___ (01)

5. What failure modes and forming process problems are most important for each lightweight material? (most important modes/problems = 5)

	High Strength Steels		Wrought Aluminum	
	Trials	Production	Trials	Production
Edge Cracking	3.9 (46)	3.9 (43)	3.5 (17)	3.4 (23)
Hole Expansion/Extrusion	3.6 (39)	3.7 (35)	3.1 (13)	3.1 (17)
Excessive Springback	4.2 (50)	4.0 (44)	3.8 (20)	3.6 (24)
Wrinkling/Buckling/ Loose Metal	4.1 (46)	4.0 (46)	3.9 (15)	3.9 (21)
Lack of Shape Fixation/ Surface Springback	3.9 (47)	3.8 (44)	3.6 (19)	3.7 (24)
Excessive Galling	2.2 (33)	2.6 (32)	3.5 (16)	3.9 (22)
Stretch Failures	3.5 (40)	3.5 (37)	3.8 (18)	3.7 (22)
Lack of Surface Quality	2.6 (33)	2.9 (32)	3.4 (16)	3.2 (21)
Blanking/Trimming Problems	2.4 (37)	2.3 (33)	2.4 (14)	2.2 (29)
Lack of Press Capacity	1.9 (32)	2.0 (30)	2.0 (15)	2.2 (19)
Choice of Lubricant	2.7 (40)	2.8 (36)	3.2 (17)	3.4 (24)
Handling/Slivers, etc.	1.7 (30)	2.2 (29)	3.0 (17)	3.0 (21)
Die Wear	2.3 (31)	3.0 (31)	2.7 (18)	2.9 (21)
Other ______	-	-	-	-