Warm Forming — Principles, Applications, Case Study

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abstract
This paper introduces the warm forming technology. The most appropriate applications for warm forming are discussed as well as its advantages and disadvantages compared to alternative manufacturing methods. Also a case study is cited to illustrate how large production volumes of technically demanding parts can be economically manufactured by warm forming.

terms
Warm Forming
Cold Forming
Forming
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1. Introduction

Metal flow forming/forging has always played an important part in manufacturing a wide range of products for the automobile industry. In addition to conventional hot forging and cold forming, the last twenty years or so has seen an increase in the use of warm forming technologies, especially due to the cost savings achieved by near-net warm forming.

For certain automotive components warm forming, usually combined with cold forming, has become a very economical manufacturing alternative especially where annual volumes are quite large such as those in the USA, Europe, Japan and Korea.

We will discuss here the most appropriate applications for warm forming as well as its characteristics, special requirements and its advantages and disadvantages compared to alternative manufacturing methods.

Finally, we will cite a case study to illustrate how large production volumes of technically demanding parts can be economically manufactured by warm forming.

2. Basic Principles of Warm Forming

The designation warm forming is applied to a forming process performed with slugs heated to temperatures between 550 and 850° Celsius or 1020 and 1560° Fahrenheit, in which a significant reduction of forming forces can be achieved relative to cold forming.

Warm forming mainly involves ferrous metals with relatively high carbon content (more than 0.3%) and higher alloy content (more than 3%). For austenitic steels, where blue brittleness does not occur, a heating range of 400 to 450° Celsius or 750 to 840° Fahrenheit applies. The temperature range between 550 and 850° Celsius or 1020 and 1560° Fahrenheit is not recommended for austenitic steels due to the lack of suitable lubricants for such applications, but warm forming of austenitic steels (e.g. stainless) is more difficult than warm forming of ferrous steels and, therefore, is seldom done.

**Figure 1** [1] illustrates the relation for yield stress, deformability and scale development for a ferrous steel subjected to heat. Two areas can be distinguished along the cruvex of the deformation capacity which are not suitable for forming.

First Area:

Below 550° C or 1020°F:
In this area an age-hardening maximum, the so-called blue brittleness appears. With low allowed steels, e.g. SAE1020 its occurrence is mainly subject to the deformation velocity. Therefore, the blue brittleness shifts to higher temperatures with increasing deformation velocity. The range of blue brittleness is not adequate for forming as deformation is even smaller than at room temperature (higher risk of cracking).
Second Area:

At 800°C or 1470°F a minimum of deformation capacity appears – “red brittleness” – but can be of interest because, first deformability can be 2.5 times (up to f =4.5) as compared to ambient temperature and second the yield stress is nearly constant between 780 - 820°C or 1440 - 1510°F. With modern induction heating equipment a temperature tolerance of +/- 10°C or +/- 50°F can be achieved. That means if there is no fluctuation in yield stress there is no fluctuation in the press force which result in more accurate, near net or net shape components. The upper temperature limit of 850°C or 1560°F for warm forming of ferrous steel is determined by the appearance of scale [2]. This increase in formability as compared to cold forming generally permits: 1) a reduction in the number of forming stations required, 2) a reduction of the nominal tonnage required, 3) fewer intermediate material treatments (heat and surface treatments) and 4) it also permits forming of steels not suitable for cold forming, e.g. Cf 53 (AISI 1053) [3].

In summary, it can be said that warm forming combines the advantages of cold forming and hot forging. By exploiting the greater formability of heated steels it is possible to achieve accuracy’s similar to those achieved by cold forming. With subsequent cold calibrating/sizing operations after warm forming the same degree of accuracy is achieved as in cold forming.

Compared to hot forging, warm forming technologies offer the following advantages:

- Reduced energy costs
- No scale
- No flash
- Better grain structure (for certain parts subsequent normalizing is unnecessary)
- Better surface quality
- Closer tolerances
- Less subsequent machining
  (material savings of up 25% can be realized => near-net forming)
- Higher production rates (compared to conventional forging presses).

These advantages make warm forming very suitable for a certain range of parts, but this part range is limited due to certain economical and technical reasons, e.g. component sizes or shapes. Thus, warm forming can only be substituted for hot forging to a limited extent.

Schuler started testing warm forming applications about twenty years ago. The first of such equipment was supplied in 1980. At that time the temperature range was between 680 and 720°C or 1260 and 1330°F. Today warm forming is typically done at temperatures between 760 and 820°C or 1400 and 1500°F.

Based on data collected on the equipment supplied to date we have acquired a significant amount of experience about where this somewhat complicated forming process can be economically applied. We will now mentioned some of the relevant factors, which need to be considered.
2.1 Part Range

Warm formed components are usually those that would otherwise be made by hot forging, primarily rotationally symmetrical parts. Also cold formed parts with a material change enable them to inductive hardening e.g. CVJs. In addition, also parts where filling is critical in cold forming and the carbon content is larger then 0.5\% C and alloys are larger than 3\%.

A closed die is used for the warm forming process, producing near-net components with no burr or flash. Tool loading ranges between 900 and 1600 N/mm\(^2\) or 130,000 to 230,000 psi. Irregular shapes or cross-sections run the risk of fracture. Sharp edges and difficult transitions are to be avoided. Advantages over cold forming include the ability to process larger and heavier parts and a more favorable heat distribution in the tooling with such larger part dimensions.

Warm formed parts usually range between 0.5 and 5 kg or one (1) to 11 pounds, generally processed on multi-station mechanical presses. Part diameter ranges from 40 to 120 mm or 1.5 to 4.7 inch depending on the available press capacity. The maximum length of the components depends on the available slide stroke, but is typically no more than 300 mm or about 12 inches. Approx. 80\% of warm formed components are for the automotive industry, e.g. CVJs, flanges, alternator pole pieces, bevel gears, etc. as well as ball bearing components and parts for the hand tool industry (e.g. socket wrench inserts).

Figure 2 illustrates the range of parts manufactured by warm forming.

Parts weighing less than about 0.5 kg or one pound should only be warm formed if cold forming is not possible due to high carbon or high alloy content. Parts weighting more than 5 kg or 11 pounds, larger than can be handled by mechanical presses, may be warm formed on hydraulic presses even though the longer contact time between tooling and part tends to reduce tool service life. In any case, the percentage of such large parts in warm forming is quite small.

2.2 Steel Composition

Warm forming typically uses ferrous steels with a carbon content no greater than 1.0\% and a proportion of alloy elements of less than 10\%.

2.3 Achievable Accuracy

Accuracy is largely dependent on part geometry and any associated problems of cooling, lubrication or tool wear. Typical accuracy is IT 11-12, with subsequent cold sizing IT9-10 or even IT 8 can be achieved (Figure 3).
Surface Quality

Surface quality (Figure 4) is largely dependent on the effectiveness of the lubrication. With proper lubrication values range between 10 and 20 micrometer (400 and 800 micro-inch or with subsequent cold sizing 6-12 micrometer (240-480 micro-inch).

2.4 Economical Batch Sizes

Compared to cold forming additional influences (part temperature, tool heating) must be considered in warm forming. To maintain optimal forming temperatures processing should not be interrupted, that is, processing is generally done on multi-station presses. Development of such tooling and the time required for testing to optimize cooling and lubrication result in high costs as compared to cold forming or hot forging. These development costs can only be recovered with corresponding large volume production (more than 200,000 parts per year). Batch sizes should also be relatively large since not only the press but also the induction heating unit has to be changed over to accommodate different slug diameters. We recommend at least one shift per batch size (approx. 8,000 to 10,000 parts). Typical batch sizes range from 30,000 to 40,000 parts.

Such installations are usually fully automated and it is very important that die change and die setting operations are optimized. There are still possibilities for reducing tool change times, but these should be weighed in terms of the cost-benefit ratio.

3. Tooling for Warm Forming

The combination of relatively high forming temperatures and considerable forming forces makes the selection of proper tool material and tool lay-out for warm forming more complicated than cold forming and hot forging. Contact tool components are subjected to considerable loads and also to thermal, tribological and chemical stresses that lead to continuous wear.

Thus, the following criteria for tooling need to be addressed [4]:

- Deformation resistance
- Resistance to breakage
- Wear resistance
- Tempering consistency
- Thermal shock resistance
- Costs

Cooling of the tools becomes very important in order to prevent the age hardening effects of the tool material used in warm forming.

High speed steel (e.g. 1.3343, 1.3344 or M2, M3/2) are used if high tool loads are dominant. The disadvantage is that these materials are not thermo shock resistant.

If production numbers are higher, warm working steels with higher thermal shock resistance (and therefore suitable for fast, direct cooling) are used for tools. These include 1.2367 (X40CrMoV53) for punches and dies, hardness 54-56 HRC and 1.2365 (X32CrMoV33 or H10) for counterpunches, hardness 54-56 HRC. The higher heat is compensated for by a more efficient cooling system. This
additional expense is justified by increased production output. Higher production output does not, of course, exclude the use of high-speed steel tools whenever they are not subject to excessive temperature or the cooling time is increased by manufacturing in alternate stroke, i.e. every second stroke one part. Warm forming steels are usually nitrat ed (short-term nitrating); PVD coating e.g. CrN suitable up to 600° C or 1110° F tool temperature or TiAlN up to 680°C or 1260° F of tool temperature.

Excellent tool service life can be achieved with the so-called “superalloy” Inconell 718 which is a high-temperature nickel alloy characterized by high temperature shock resistance, high resistance to breakage and high fatigue strength [5].

Even though carbide steels are very well suited for the forming process itself, they are not used in warm forming as they fail after any interruption of the process and the resulting temperature drop.

During warm forming the specific load on the tooling is approx. 50-60% of that found in cold forming and about twice that found in hot forging. Tool layout is similar to that found in cold forming tools. The dies are preloaded (stress ring material e.g. 1.2714, 1.2343 or 57 NiCrMo V7 similar to 6F2 x32 CrMoV51=H13. Additional coolant supply and discharge grooves or bores must be provided. **Figure 5** is an example of tooling for warm forming.

**Tool service life or wear**

Tool service life or wear is largely dependent on part geometry, expected tolerances and tool cooling and lubrication. Production downtimes are mainly caused by tool wear. Critical tool components are, for example, dies for full forward extrusion and forming punches for backward extrusion. For the widely used warm forming steel tools the wear on these components is approx. 0.2 mm or 0.008 inch per 10,000 parts; for tool components with normal heat loading wear is approx. 0.05-0.1 mm or 0.002 to 0.004 inch per 10,000 parts.

Result: The larger the permissible tolerances, the longer the tool service life. Generally the process is designed in such a way that only about 60 to 80% of the maximum permissible tool loading is used. If optimal cooling is not possible (due to tool layout) thermal overload can occur.

4. **Cooling/Lubrication of Warm Forming Tools**

Along with know-how in tool layout and design of the part progression, cooling and lubrication is extremely important for economical use of the warm forming process. The problem is that optimal lubrication leads to problems with cooling and optimal cooling considerably limits effective lubrication. These are facts that have to be accepted.
Nowadays graphite-force lubricants (Adreson, Fuchs, Bechem) are used for warm forming applications and cup parts have to be pre-graphite coated with e.g. Delta forge 31 before the final heating in the induction heater. For normal applications short, flat parts, cooling/lubrication is carried out simultaneously (by flooding). But for shafts and difficult extrusion operations a more sophisticated cooling/lubrication system is needed. A special spraying system with compressed air makes use of the relatively long cycle time for the return stroke and part of the downward stroke of the slide for cooling and the relatively short time of the downward stroke of the slide for lubricating. Figure 6 illustrates such a spraying system. Individual adjustment of coolant and lubricant for each station has to be provided. Time control is generally sufficient. (Figure 7 [6]). Only in exceptional cases does the quantity have to be controlled.

5 Peripherals

5.1 Manufacture and Pre-treatment of Slugs

Since these are mainly closed die applications, a typical weight tolerance is +/- 0.5%. This tolerance can only be achieved with a raw material diameter quality of h₁₂ or smaller diameter tolerances. There are also rather narrow tolerances for the shearing or sawing quality. Maximum length tolerances has to be less than 0.3 mm (0.012 inch) or 0.1 mm (0.004 inch) for closed die applications. If these conditions cannot be met, parts have to be sorted according to weight range (e.g. two batches whereby lighter parts are used for new tooling and heavier parts are used with tooling with some wear).

Using peeled material, shotblasting of the surface or tumbling of the parts is appropriate. Shotblasting or tumbling eliminates sharp edges and possible burr caused by shearing or sawing. Sharp edges can lead to faster tool wear, especially during forward extrusion.

Hot rolled steels are used. A rust and scale-free surface is important. When manufacturing shaft components the slugs are graphite-coated prior to forming since this coating results in improved tool service life, especially for full forward and backward extrusion.

5.2 Induction Heating

The induction heating equipment includes a static converter, automatic part feeder (graphite-coated slugs can only be fed via elevator), re-cooling unit and temperature monitoring. The loading system between heater and press should be equipped with a discharge chute for improperly heated parts. These rejected parts can be re-fed after an additional shotblasting operation. The heating should be done in a coil with a temperature maintenance of adequate length.

Required energy supply: 0.21 to 0.24 kW x hr/kg material (0.1-0.11 kW x hr/lbs)

Appropriate options for the induction heater include:

- weight monitoring
Automated press installations are equipped with monitoring device which prevent processing of parts which are either too small or too large. A machine stop for this reason would mean a loss of time (approx. ten minutes) and a loss of quality (due to a change in the temperature of the tooling). Thus every attempt should be made to avoid feeding such parts into the press.

☐ Spray coating with graphite (e.g. Delta forge 31)

This unit is installed between the automatic feeder and the induction heater and consists of a smaller induction heater to preheat the parts to approx. 180° C or 360° F and a spraying unit.

The parts are completely coated. The parts with their graphite coating enter the induction heater. Here, approx. 30-50% of the coating is burned off, but what remains, in conjunction with the additional lubricant from the tool lubrication system, acts as a separating agent, especially useful during extruding operations such as full forward extrusion and reducing in the first two stations. The result is also a considerable increase in tool service life.

5.3 Press

Automatic multi-station presses are recommended for warm-forming applications, with a transfer system, integrated cooling/lubricating system for tools and mechanically-operated bed and slide ejectors. Such production lines typically operate in continuous run mode with an output rate of 20-40 parts per minute.

6 Case Study

The following case study from Daimler-Chrysler illustrates an application of warm forming technology. Axle flanges (Figure 8) for passenger cars with rear wheel drive, material Ck 45 (AISI 1045), are designed to transmit torque between differential gear and wheels.

Very precise forming of the inner contour with very little eccentricity is important for the proper functioning of these parts.

Previous Production Method

Previously these parts were produced on a conventional vertical forging press with approx. 1600-ton nominal press force in automated single stroke with an output of approx. 15 parts per minute. Sheared, hot rolled bar stock with a diameter tolerance of h₁₃ was first heated to forging temperature (1050-1100° C or 1920-2010° F) and hot forged in three stations as follows:

Station 1: Upsetting with descaling
Station 2: Preforming
Station 3: Forming
The forming process was followed by flash trimming and thermal treatment (normalizing). After secondary machining operations the parts also had to be balanced to correct the considerable degree of eccentricity, which cannot be avoided in forging.

The manufacturing process described here, especially the thermal treatment, the secondary machining and balancing, was very expensive. Thus, Daimler-Chrysler was looking for a more economical alternative method. This alternative method was found in warm forming.

**Current Manufacturing Method**

For the past several years Daimler-Chrysler has been producing the axles flanges on a vertical five-station press with 1250-ton nominal press force at 40 spm and 20 ppm output (one part is produced on every second stroke).

Three facts explain why the warm-forming press has a lower nominal capacity than the forging press even though the deformation stresses are high in warm forming.

- Producing one part on every second stroke
- Warm forming technology is closed die forming without flash which means that the forming surface is smaller and require less forming force.
- The specially designed warm-forming presses are able to better handle off-center loading than forging presses.

Raw material for the warm forming of axle flanges is hot rolled bar stock with a diameter tolerance of h₁₂. After shearing the slugs are preheated to approx. 180° C or 360° and fed into a submersion bath for graphite precoating. Then they are heated in the induction heater to the forming temperature of approx. 780° C or 1440° F and fed into the press, to be warmed in five stations.

The progression (Figure 9) is as follows:

Station 1: Full forward extrusion (required press force: approx. 100 ton)
Station 2: Upsetting (required press force: approx. 420 ton)
Station 3: Centering (required press force: approx. 580 tons)
Station 4: Contour preforming (required press force: approx. 720 ton)
Station 5: Calibrating (required press force: approx. 400 ton)

The warm-forming tool material is a warm working steel, e.g. 1.2367 (X40CrMoV53). For cooling/lubrication a flooding system is used (with volume control). The emulsion is a circulating graphite-vegetable oil emulsion of two or three parts water on one part graphite-vegetable oil.

After warm forming no further thermal treatment, e.g. normalizing, is required due to the controlled cooling of the parts by means of a special unloading conveyor. Because of the very precise near-net forming (Figure 10) the cost of secondary machining is reduced by approx. 25% compared to hot forged parts. The minimal eccentricity of the inner contour makes a final balancing operation unnecessary.

**Cost Savings Associated with Warm Forming**
A thorough comparison between forging and warm forming of axle flanges requires consideration of quite a variety of costs and facts.

Even though the warm forming press with its 1250-ton nominal force capacity is smaller than the vertical forging press with 1600-ton force, the cost of the press and hourly rates are nearly identical. This is due to the more expensive cooling/lubricating system, the number of stations and a longer slide stroke on the 1250-ton warm forming press. (For continuous run operation slide stroke needs to be four times as long as the slug.)

Costs for coolant/lubricant are nearly the same for both methods.

The manufacturing cost of the warm forming tooling is nearly two-and-a-half times as high as those for the forging press, but this is offset by the longer tool service life which exceeds forging tool life by three or four times.

The warm-forming press demonstrates a slight cost disadvantage in terms of raw material and the required shearing device since the slugs produced has to be of higher quality. On the other hand, warm forming instead of forging results in material savings of approximately 10%.

A comparison of the heating requirements of forging vs. warm forming shows no advantage for either method. Although the slugs for forging have to be heated to a higher temperature, the required inductor capacity is not much higher due to an approx. 25% lower throughput. Moreover, the warm forming line, in addition to the induction heater, also require a precoating unit of the slugs with graphite.

The significant cost savings in warm forming, in addition to the 10% savings, include increased output by 1/3, the elimination of secondary heat treatment (normalizing) and balancing as well as the 25% reduction in machining costs. These numbers induced Daimler-Chrysler to choose the warm-forming technology for the manufacture of axle flanges since warm forming results in an overall reduction of manufacturing costs by approx. 20% for these specific parts.

7 Summary

The aim of this paper was an introduction to the warm forming process. It illustrated which parts can be economically produced by this method and provided one case study.

Finally, it should be pointed out again that even though warm forming is an attractive alternative to forging and cold forming, it can never completely substitute for these methods. By expanding the range of parts suitable for warm forming, this process, often in combination with cold forming, offers a very economical manufacturing alternative for a certain part range, especially where large volumes are concerned.
8  Index of Illustrations

Yield Stress, Deformability and Scale Development

For Material C15 or SAE 1015 Subject to Temperature

Figure 1: Yield Stress, Deformability and Development of Scale for C15 (AISI 1015) Subject to Temperature

Warm and Cold Formed Parts

Figure 2: Parts Produced by Warm Forming Method
Comparison of tolerances

<table>
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<th>Process</th>
<th>Area</th>
<th>Achievable Tolerances „IT“</th>
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Figure 3: Comparison of Tolerances

Achievable Surface Quality

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<td>Rt: 12-24 μm</td>
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<td>combination warm / cold (sizing)</td>
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<td>extrusion</td>
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Figure 4: Achievable Surface Quality
Figure 5: Tool Design for Warm Forming (example: Bell Shaft)

Figure 6: Lubricating/Cooling with Spray Rings
Figure 7: Control Diagram – Spray System

Figure 8: Finished Part "Axle Flange"
Figure 9: Progression Drawing of Part "Axle Flange"

Figure 10: Formed Part Drawing of Part "Axle Flange"
9 Literature

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