

Shape Memory Material Manufacturing Design Optimization and Stress Analysis

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Abstract: A recent breakthrough in the development of shape memory materials has demonstrated promising applications for completion products in the oil and gas industry. In one of the targeted applications, shape modification is a major step toward commercialization of this technology. Efficiently and effectively reshaping the material is a key element for final production. The goal of our technical team is to design and optimize the reshaping equipment so as to enable production quantities of tools while maintaining material properties. Many factors could affect the reshaping of the shape memory material such as reshaping profile, length, available compaction force, compaction speed, shear deformation, and damage to the material. In order to achieve better understanding and obtain optimized parameters, material reshaping was extensively investigated through numerical modeling and advanced finite element analysis. This paper will cover the concepts, challenges, and finite element modeling of reshaping shape memory materials. Detailed deformation and stress distribution of the material were obtained and analyzed to guide the equipment design.

Keywords: Shape Memory Material, Completion Products, Design Optimization, Experimental Verification.

1. Introduction

The unique characteristics of shape memory materials are attractive to many applications where transition between a temporary shape and a permanent shape is necessary. In the past decades, shape memory materials have been used mostly in industrial applications, biomedical fields and other related applications. Due to the downhole harsh environment of oil and gas industry, the application of shape memory materials in this industry was limited and discovered only recently.

In our target applications, the permanent shape is desired at downhole. However, in order to achieve this permanent form, a temporary shape must be manufactured and then delivered to downhole. Thus, the reshaping process becomes a key element of the target applications. Since the manufacturing process may introduce detrimental changes to the material mechanical properties, how to minimize the manufacturing impacts becomes the major challenge of this reshaping process. More importantly, an optimized manufacturing process may yield lower cost and consume less energy while maintaining the highest productivity.

During the manufacturing process, the change of the material mechanical properties is closely related to the loading history of the shape memory materials. Thus, an understanding of the manufacturing process and further improvement of the manufacturing process could eventually help to minimize the impact of the manufacturing process. At the same time, lowering the cost and reducing the energy consumption should always be considered in order to yield maximum efficiency and productivity. As loading history is more important to the manufacturing process, it is desirable to always keep the applied loads as low as possible while maintaining certain productivity. To achieve this goal, one has to consider the manufacturing machine working speed, available load, and desired length, and at the same time, minimize the shear deformation of the materials. In order to freeze a temporary shape for downhole application, special compaction equipment has been developed to minimize the distortion of the shape memory materials. In an optimized process, as the shape memory materials pass the reshaping machine, the internal stress and shearing deformation can be kept at a minimum. The productivity is directly related to the manufacturing speed, and ultimately affects the profitability and rate of return on investment.

To fully investigate all the possible effects of the manufacturing process, a minimal amount of experimental work to understand the material characteristics is absolutely necessary. However, the study of the manufacturing process is time-consuming and expensive for each configuration, so it is not feasible to investigate all aspects of manufacturing processes through experimental work due to the time and cost constraint. Thus it makes the numerical simulation important to optimize the manufacturing process. Through the numerical simulation, a proper manufacturing profile can be designed to minimize the load and optimize the production rate while lowering the cost. For this purpose, the advanced finite element package Abaqus was used to perform the simulation of the manufacturing process. During the simulation, Abaqus/CAE was used to build the model and Abaqus/Standard was used to perform the simulation.

2. Problem description

For downhole applications, reshaping the shape memory materials can take a tremendous amount of loads. As illustrated in Figure 1, the ultimate effect of the compaction process is to compact the material onto a mandrel, and freeze the shape as a temporary shape until it reaches downhole. During the compaction, the outer diameter (OD) of the shape memory material-based product is reduced to a specified diameter so that it can be delivered and deployed downhole.

During the compaction process, in order to preserve maximum material performance, unique equipment, shape memory compactor is designed to perform this operation. As shown in Figure 2, the compactor constrains the materials while the material goes through the compactor. It should be noted that Figure 2 is only used to illustrate the concept of the compaction process while the real compactor is much more complex and has many features to protect the shape memory material and reduce the shear deformation.

Given constitutive information of the shape memory material, the goal of this investigation is to study the compactor profile effects. This includes different types of profile, such as spherical profile, exponential profile, and straight profile compactor, and the compactor length/inclusion angle. By knowing the characteristics of the compaction process, we can select the best profile and best compactor length for manufacturing process.

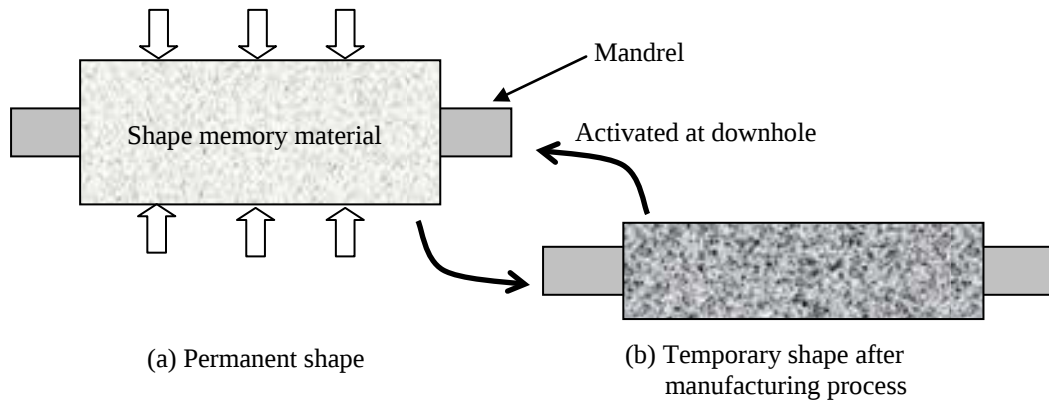


Figure 1. Concept of shape memory material reshaping process.

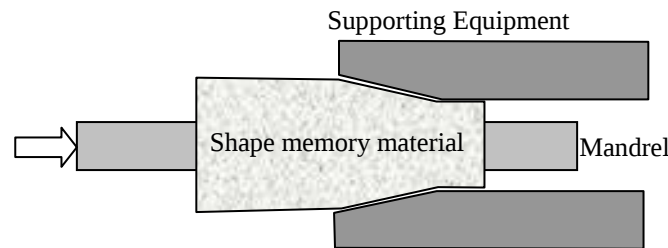


Figure 2. Schematic of compaction process.

It is worth noting that temperature can greatly affect the material properties. Thus, temperature can be another factor influencing the compactor design. In this paper, temperature is considered constant as the temperature effects can be easily derived.

3. Finite element modeling

3.1 Geometry idealization and mesh design

Due to the complexity of the compaction process, a full-scale 3D finite element model is closer to a realistic situation. However, full-scale simulation of many tiny features introduced in the compactor is very difficult under current computational capacity (for example, the characteristic length ranges from 0.02 inch to several feet). During the early study of the compaction process, it was found that a 2D axisymmetric model can greatly simplify the simulation. As discussed in the following “Boundary conditions” part, boundary conditions for a 2D axisymmetric model can be greatly simplified without sacrificing too many details of the shape memory material. More importantly, the use of a 2D model can dramatically reduce the simulation time and yield reasonable results quickly.

In this paper, the geometry consideration is mainly concerned with the shape of the manufacturing machine. To further simplify the modeling process, the compactor and the internal mandrel were modeled as rigid bodies. The profile of the compactor can be set up using different rigid body profiles. Straight profiles and spherical profiles can be modeled exactly while exponential profiles can only be modeled with spline curves through pre-set points. For the shape memory materials, it was considered as a deformable body, and meshed with hex element CAX4R.

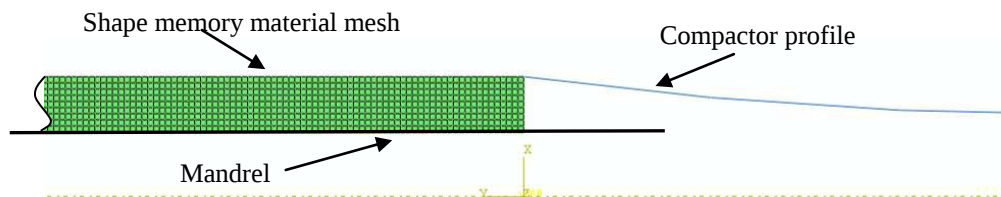


Figure 3. Typical model configuration with rigid compactor and mandrel. A spherical compactor is shown in this configuration.

3.2 Material modeling

The compaction is performed at elevated temperature to minimize the manufacturing impact. Under elevated temperature, the shape memory material behaves like hyperelastic material. Thus, the hyperelastic material model was selected for this study. To simplify the simulation, experimental testing was performed at a similar rate.

Due to the unique characteristics of this shape memory material and difficulties performing other experimental tests, only the uniaxial compression test was considered. Thus, the results from the uniaxial compressive test are the only experimental data to aid the numerical simulation. Given the limited experimental data set, Ogden strain energy potential was then selected for simulation

purpose. For example, Figure 4 shows the stress-strain relationship under 50% strain rate per minute. It should be noted that the curve has been scaled based on the yielding point stress. In this case, yielding occurs at 7% compressive strain. Testing of material was performed at different strain rate and different temperature to study the relaxation as well as the temperature effects. The results can be found elsewhere “(Feng, 2010)” and is beyond the scope of this paper.

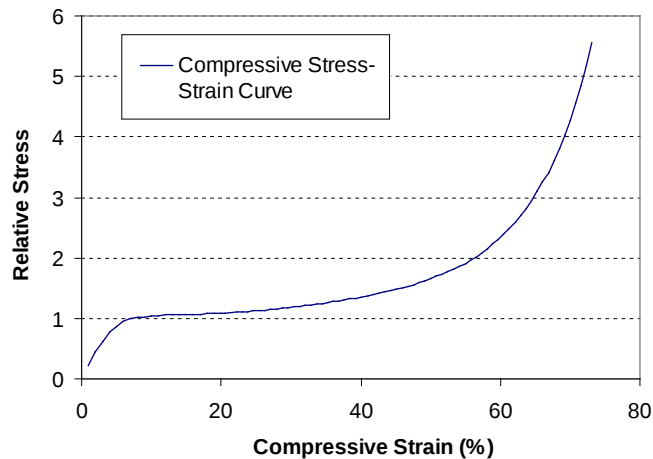


Figure 4. Typical compressive uniaxial stress-strain curve. The data has been normalized relative to the plateau point at 7% strain.

3.3 Boundary conditions

The compaction process involves a relative long working distance. It makes the simulation difficult even for 2D axisymmetric model. However, during the real compaction process, a special sheath was introduced to protect the shape memory material. Due to this special arrangement of the compaction process, the interaction between the shape memory material and compactor internal wall can be assumed to be frictionless or have very small effective friction coefficient. The consideration of an effective friction coefficient between the shape memory material and the interior of the manufacturing machine greatly simplifies the simulation process. Real friction effects were calculated by theoretically analyzing the compaction process. As for the mandrel, it is also treated as a rigid body, and implemented by restricting the movement of internal nodes. By eliminating the radial movement of the internal nodes, the material behaves like it is compacted on a rigid mandrel.

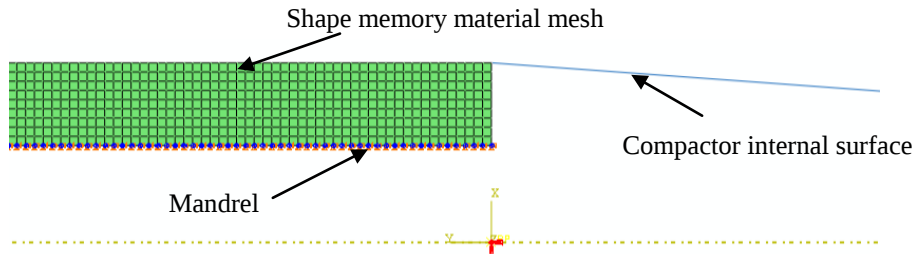


Figure 5. Boundary conditions of the compaction process.

4. Conclusions and discussions

Detailed finite element analyses were conducted on four different profiles (i.e., straight, exponential, spherical-straight combination and full spherical), three different compactor lengths (2 ft, 3 ft and 4 ft), and two assumed friction coefficients. The typical profile for a 2-ft compactor is illustrated in Figure 6. It was found that both the profile and length of the compactor could affect the required manufacturing load. Under the same configuration, finite element results indicate the spherical profile to be the worst and the straight profile to be the best choice.

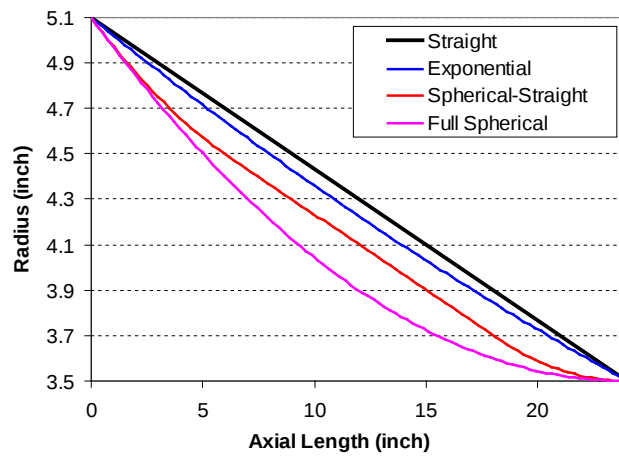


Figure 6. Typical profile consideration for a 2-ft compactor.

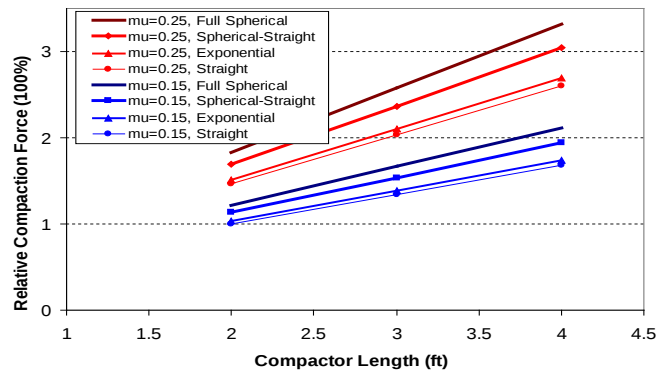


Figure 7. Comparison of compaction force for different compactor lengths.

In terms of required compaction load, it is generally in the range of tens to hundreds of thousand pounds. To further investigate the effects of different compactor profiles and lengths, the results were normalized based on the smallest compactor. As shown in Figure 7, the longer the compactor, the larger the compaction forces. The higher the profile as illustrated in Figure 6, the less the force required to reshape the materials. This implies the straight profile can serve the best for the compaction, which is different from what was initially conjectured.

As discussed earlier, increasing the manufacturing temperature can significantly reduce the loading requirement. For example, a 20°F deviation from the optimized operating temperature can easily increase (-20°F) or decrease (+20°F) the load by at least 50%. Opposite from temperature, the compaction speed effect is also monotonic. As the speed increases, i.e., the rate of production increases, the required load to reshape the shape memory material can increase dramatically from 10% to 50%, depending on the amount of increase in compaction speed. The higher the production rate, the higher the compaction loads.

Under the current configuration, not much shear deformation is observed, and most importantly, the shear deformation is quite uniform. Since the boundary conditions have been greatly simplified to ease the simulation process, questions have been raised for the fidelity of the simulation, especially concerning the shear deformation, which can be a gauging factor for the simulation. During the full-scale article manufacturing, the shear deformation on the end of the shape memory materials was closely checked. It was found that the result from finite element simulation matches closely with experimental observation, as demonstrated in Figure 8. This also confirms that, without modeling manufacturing details, the results from 2D can yield reasonable results.

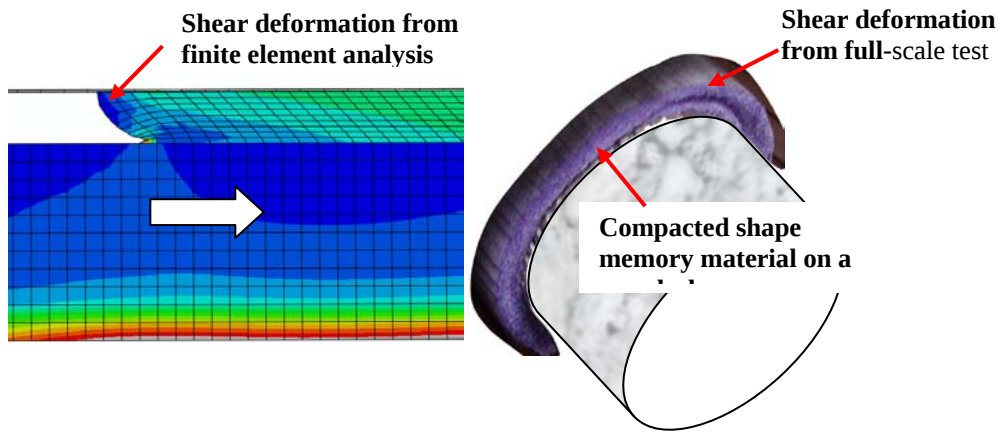


Figure 8. Comparison between finite element results and full-scale experiment.

5. References

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