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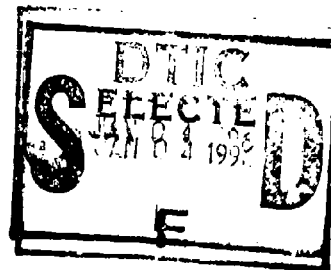
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CONTRACTING ORGANIZATION: Daum GmbH
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Surgical Robot Hand

DAMD17-94-J-4502

Dr. Ing Wolfgang Daum

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It has been shown how a surgical robot hand can be made with shape memory elements to act as driving motors.

Fundamental test have been performed to give information on the shape memory elements. These have been evaluated for their use as actuators.

A video presents the results.

Method of making a small surgical robot hand.

47

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**SUBJECT: Annual Report for Grant Number
DAMD17-94-J-4502**

SURGICAL ROBOT HAND

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A - Introduction

The object of the project is to build a robot hand, which can be inserted via a 10 mm trocar into the human body of the patient. It shall be used for general remote control manipulation.

We planed to drive the robot hand by shape memory alloy elements (sme). We still use sme as driving motors but use the in a different way as proposed. This report is structured in the following sections:

A - To give the reader a general perspective of this report.

B - To construct the robot hand we had to evaluate the sme material first.

This section describes our basic research on the sme elements.

C - This section of the report explains how the finger of the robot hand works.

It ends with an video showing the result of our research:

A smal robot finger moving fast enough to build a hand out of three of those fingers.

D - Conclusion

The video you will find is in the german format vhs. We did not have the chance to convert it to the USA standard but hope that the reader will have the opportunity to find a vhs video player. Else please have a professional convert the video to the desired format and send us the bill!



B - EXPERIMENTS AND MEASUREMENTS OF SHAPE MEMORY ELEMENTS (sme)

To make the two finger tweezer we made various experiments and measurements of NiTi and CuZnAl shape memory alloys and will explain the origins for results and observations in the following.

1. Tested material samples

Material samples are specified in paragraph 1.1 and 1.2. Specifications are based on producer's information.

1.1. NITI compression springs

This compression springs exhibit a one-way shape memory.

transformation temperature	between 50 ° and 70 ° C
diameter of wire	0,75 mm
external diameter of spring	5,80 mm
length of wire (cold)	4,50 mm
length of wire (warm)	19,00 mm
number of turns (active)	5
recommended strain by calefaction	5,0 N
recommended strain by refrigeration	2,5 N
(exceeding of recommended strains is disadvantageous to life-span)	

1.2. CuZnAl bending elements

Bending elements exhibit a two-way shape memory .

transformation temperature	As $\approx$ 65 ° C	Af $\approx$ 80 ° C
	Ms $\approx$ 65 ° C	Mf $\approx$ 55 ° C
total length	40,0 mm	
clamping length	6,0 mm	
free length	34,0 mm	
thickness	,80 mm	
breadth	8,0 mm	
recommended strain on free end	1 N	



way on free end 10,0 mm
(exceeding of recommended strains is disadvantageous to life-span)

2. Temperature-way-characteristics

Measurements described below should determine exactly the course of the temperature-way-characteristic of shape-memory samples. In the same way producer's data could be reviewed. All characteristics indicated in various literature are certainly considerably idealized.

The experiment was arranged on the following way. Arithmetic paper was glued on the bottom of a level vessel. Samples were clamped with one side in a small fixture and put on the bottom of said vessel. Then, the vessel was filled up with water so that the samples were covered and put on a hot-plate. In this way, constant heating and cooling of the samples are granted and considerable abrupt variations in temperature are avoided. Water was heated and cooled while permanently stirring up it so that differences in temperature inside the vessel are as small as possible.

Temperature was controlled by a digital thermometer.

In this manner, certain temperatures were related to certain lengths of way, which were covered by the samples because of shape change. All temperature-way-characteristics of paragraph 2.1. to 2.3. were made with this method. At the start- and endpoints of all characteristics we found relative big measurement errors because, at these points it is difficult to perceive, in which points of temperature a change of way begins or ends.

2.1. Hysteresis of CuZnAl bending elements

CuZnAl bending elements show a two-way shape memory. Temperature-way-characteristic can be considered as hysteresis. Characteristics in figures 1 to 4 show the results of each series of measurement. In figure 5 all this characteristics are shown on one page in order to have the possibility to compare them. Figure 5 shows, that no certain temperature can be related to a certain way.

For the measurements in figures 1 and 2 was used one and the same sample. In figure 1 the characteristic of the bending element after a "longer" storage was taken during the first thermal cycle. Characteristic of figure 2 was taken a short time later during the second thermal cycle. For the characteristics in figures 3 and 4 we used other samples, but they were subject to a thermal



cycle a short time before.

Interpretation:

In figures 1 and 2, the hysteresises are different. Temperatures of starting and end points are in figure 1 considerably higher. Besides, the hysteresis there is enlarged. But the characteristic was taken with the same sample. The arrangement of the experiment can be supposed as origin of this difference. The only difference in the arrangement of these experiments consist in that the characteristic of figure 1 was taken after "longer" storage during first thermal cycle, characteristic in figure 2 during the second.

It can be assumed, that shape memory alloys forget their shape memory after longer storage. During heating, they remember their learned shape effect only by considerable high temperatures. The enlargement of the hysteresis in figure 1 can be explained by this inertia. The tested bending element of figure 2 shows an elongation of only 9 mm instead of 10 mm as indicated by producer. It can be expected, that the shape memory of this sample was not optimal and for this reason the total possible shape change could not be achieved.

In figures 2 to 4 following average transformation temperatures were determined:

$A_s \approx 62^\circ \text{C}$	$A_f \approx 81^\circ \text{C}$
$M_s \approx 76^\circ \text{C}$	$M_f \approx 54^\circ \text{C}$

If this transformation temperatures are compared with producer's data, indicated in paragraph 1.2, there can be observed divergences. Origin of this divergences could be reading errors, mentioned in paragraph 1.2., which can occur just by starting and finish temperatures.

Bending elements exhibits the biggest shape change per degree Kelvin in heating phase by 75°C with 4-7 mm elongation and in cooling phase by 67°C with 5-6 mm elongation (determined in figures 2 - 4).

2.2. Characteristics of NiTi compression springs (compressed)

For compression springs it is necessary to define a initial (zero) position in order to give a correct interpretation of characteristics in paragraph 2.2 and 2.3. As initial (zero) position is defined the position of the NiTi springs when heating is started. Because these NiTi springs exhibit a one-way shape memory, there is no shape change by following cooling. These springs can be compressed



and stretched in "cold" state by external forces. They keep their forced state until they will be heated and than initial position will be achieved.

In our experiment the NiTi springs were compressed in cold state and the elongation is indicated in the characteristic as negative value. While heating the initial position is obtained. Figures 6 - 9 show the separate characteristics of various NiTi springs. In figure 10 they are shown side by side for better comparison of values.

2.3. Characteristics of NiTi compression springs (stretched)

Here is defined the same initial position of the compression springs as described in paragraph 1.2. In cold state, the springs are stretched before heating begins. Elongation is indicated as positive value. While heating, the initial position is obtained.

These springs can be easily stretched, but compressed only until the point that one turn touches the other. In figures 11 - 14 are shown the separate characteristics of various NiTi springs. Figure 15 shows the characteristics on one page for better comparison.

3. Possibilities for cooling

3.1. Cooling by means of flexible tubes

For this experiment one flexible tube was fixed on the shape memory specimen. Figure 23a shows a cross sectional view of arrangement for cooling by two flexible tubes through which a cooling liquid is pumped. Flexible tubes are charged with water. On this manner it is possible to cool the shape memory specimen. It is also possible to heat them, because both tubes can be charged either by cool or by hot water. This method was successfull.

For a better heat transmission we glued a flexible half circle profile tube on the shape memory specimen. Figure 23b shows a cross sectional view of arrangement for cooling by one flexible profile tube. This profile tube was also charged by cool and hot water. This method of cooling and heating was more effective than the first method, mentioned above.



3.2. Cooling by Peltier elements

Peltier elements in combination of Seebeck and Peltier effect produce in dependence of polarity cooling or heating at the junctions of the thermocouples of two conductors or semiconductors on condition of current passage. These thermoelectrical components are used as cooling elements e.g. in other electronic components or small refrigerators. Construction of a Peltier element is shown in figure 23c.

3.3. Peltier elements

Single-stage Peltier elements (figure 23d,e) can obtain a maximal ΔT between both ceramic surfaces of about 65 K. This ΔT is partitioned equally over the ambient temperature. Life-span amounts to usually 100 000 hours, if working and storage temperatures amounts to maximum 80 ° C. If temperatures are higher cooling elements strain faster because copper molecules diffuse into the semiconductor material. Besides, there arises the possibility, that the soldered joint between copper and ceramics smelts. Melting point of tin-bismuth-solder is lower than 136 ° C.

It is very important to keep the Peltier elements dry because they can corrode very fast in case of moisture. For the amelioration of thermal contact between the object to be cooled and the cooling element it is advantageous to use a layer of thermal conduction mass with thickness less than 0,025 mm. Accordingly, the surface roughness of the element to be cooled should amount to 0,7 - 1,7 μm , which is adequate to fine emery.

Peltier elements can be soldered at their ceramic surfaces. But because there arises thermoelectric voltages, it is useful to do that only for ceramic surfaces with dimensions up to 15 mm x 15 mm. Producer recommends to use a solder of indium (52 %) and tin (48 %).

3.4. Experiments for cooling with Peltier elements

Theoretically, Peltier elements are only conditionally suitable for cooling of CuZnAl-bending elements, because heating of the Peltier element to a temperature higher than 80 ° C should be avoided. But the Af temperature of our shape memory alloy amounts to 80 ° C. For a "commercial" cooling with Peltier elements should be used such shape memory alloys, which transformation temperature is minimum 5 K lower. Using this thermoelectrical elements such a bending element



could be not only cooled, but also heated in case of pole reversal of electrical connections.

For following experiments Peltier elements with dimensions 8x8x4 were applied. If they are put on the bending element, it is less practical, because they do not sit closely on the bending element, but have contact only in one point.

For making this method more effective, Peltier elements were cut between n- and p- conductors with a diamond charged cutting-off wheel in small strips. These strips were glued side by side on the CuZnAl-bending element and connected one with each other electrically (see figure 23f). On this manner, the bending element can be heated and cooled on an accelerated way.

The most effective cooling methode would be possible with flexible Peltier elements. But producers or suppliers do not deliver such elements. Therefore we tried to produce such a flexible cooling elements ourselves. We decomposed Peltier elements and sorted ist pieces accordingly to n- and p-conductors. The copper bridges were replaced by flexible copperplates, on which the n- and p-conductors were solded by bismuth-tin (see figure 23f).

The ceramic plates were eliminated completely. For practical use it is necessary to isolate cooling element electrically from bending element. The lower flexible cooperplates can be replaced also by a structured coppercoated printed card. First experiments showed, that this flexible Peltier element functions like a conventional Peltier element and therefore it should show the best cooling.

3.5. Comparison of cooling variants

Cooling by flexible tubes which are filled with a cooling fluid is very effective, but a big number of feeding and discharging tubes plus pump are necessary. Besides, this variant demands additional valves and a control system in order to move each memory part of a whole system of suchlikes. Many complex components would be necessary for a movement of a relative simple system of shape memory alloys.

In opposition to it cooling with Peltier elements cut in strips (flexible Peltier elements) seems to be a very good solution. Shape memory elements can be cooled and heated very simply. Only a supply point and an electronical control system are necessary for this variant. But this solution is not as well as it seems to be at first sight. The experiments show that it is not simple to keep a big value of ΔT over a long time between the warm and the cold side of the Peltier element. In order



to have the possibility for permanent cooling, it is necessary to take away the heat from the warm side. Glued cooling ribs caused a considerable amelioration of that cooling.

Up to now, further possibilities for a fast and effective cooling of shape memory alloys were not found. It is necessary to make further experiments on this area.

4. Training of sme elements

The shape memory effect is not given to the springs per se. Therefore a training mechanism was evaluated to give desired shape memory. We will discuss this subject in more detail in the next report but will show here first results of our tests. Basically the training has to be done under certain temperature-deformation conditions where the temperature is changed from one deformation to the other. Figure 16 to 20 shows sme elements after different training conditions. These results are combined to show in figure 21. Figure 22 underlines the effect of training. Shown is the ability of a sme to memorize the shape after different temperature-deformation circles.



C - BUILDING A SURGICAL ROBOT HAND

The video is in the german format VHS, which we are not able to convert to NTSC. If you are not able to watch the video, please have it converted to your format and send us the bill.

1. Two-Finger-Tweezer

In the first sequence of the video is shown a two finger tweezer of large size. Fingerlenth is about 18 cm, diameter if finger 1 cm.

Figure 24 shows the construction of each finger. Each finger comprises 4 segments, each having 3 sme. These sme will be heated by indirect electrical current. The electrical current will pass electrical conducting rubber which will heat up under those conditior s. Because of the good uninterrupted interface between sme and rubber heat will flow into the sme to heat up sme. Each sme can be connected individually by driver electronics. MOSFET drivers are shown schematically in figure 25 of the report. The amount of current is controlled by puls-wide-function in current, figure 26. We constuctad an electronical board to interface the tweezer to an IBM compatible computer, figure 27.

The tweezer can be controlled by pressing certain keys at the keyboard of the controlling computer. One the upper left side of the first sequence of the video one can see the tweezerfinger as indicated on the computerscreen. The operator will move the points 1 - 4 of the finger individually by the keyboard to controll the finger unit. The programm itself will decide which element of the 12 to heat in order to move the finger in the desired way.

It seems obvious that the tweezer moves very slow. We have not added cooling devices such as described in paragraph B to this device.

2. Long sme wire to act as an muscle

In figure 28 you can see a setup of the experiment shown in the second sequence of 'he video. Shown is a tube 1 which is conected via pivoaxis 8 to a wheel 2 which itself is close conected to a second tube 3. Second tube acts as an arm to hold the weight 4 of 400 g. A shape memory wire 5 is connected from point 7 inside the tube 1 via hole 9 around wheel 2 to point 6. Not shown here is the electrical connection which can be directly inserted through the sme wire 5. If the wire is heated, it will contract and lift the weight 4. This is shown in the second sequence of the video.



3. Small Robot Hand

Such an sme wire 5 will therefore act as an muscle. The weight 4 will always pull back the wire when not heated anymore to lengthen it. Instead of the weight, a second sme wire could pull back the first one. This has proved to be a good principle of moving fingers of small robot hands.

In figures 29 to 33 is shown the construction of the robot hand show in the third and last sequence of the video. All measurements are in millimeters. It is a mechanical hand, 9,5 mm in diameter to pas through a medical trocar, with 3 fingers each comprising two phalanxes. Each phalanx is connected to two sme wires which work against each other in the sense explained above. These sme wires are located in the tube (shaft) holding the robot hand. The video shows just one phalanx of one finger moving. We cab only show this one phalanx, because we just got to this point. But it now seems easy to add more sme wires to the hand unit to complete it. This is underlined by the fact, that we already completed the hand itself. Just the driving motor sme-wire has to be added.

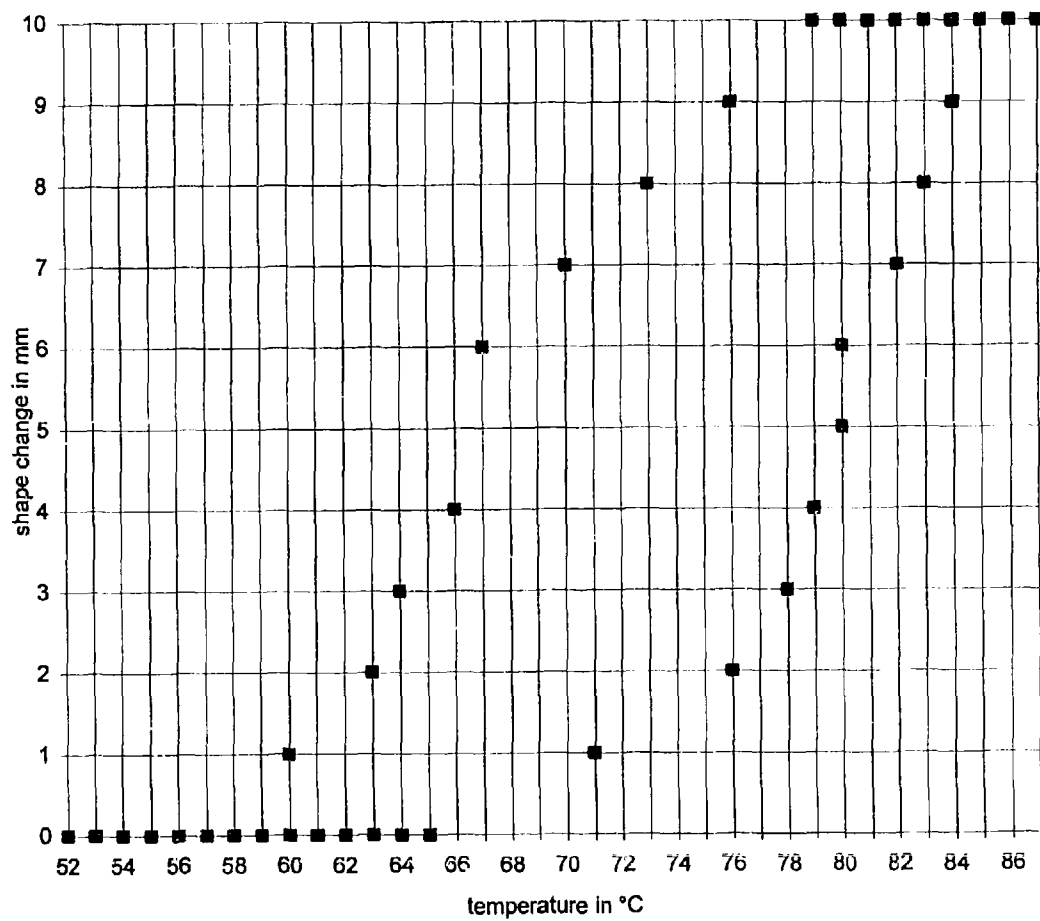
The robot hand got a glove around it for the reason to protect the mechanic of the device from blood coagulation. This device and the moving mechanism is about to be filed for patent!!

D - CONCLUSION

A small 3 finger robot hand could be demonstrated with yet only one phalanx to move. It was shown how basic experiments where done in order to evaluate the shape memory elements to act as the driving motor for the hand device. It is only a matter of time untill the second report to demonstrate the whole hand.

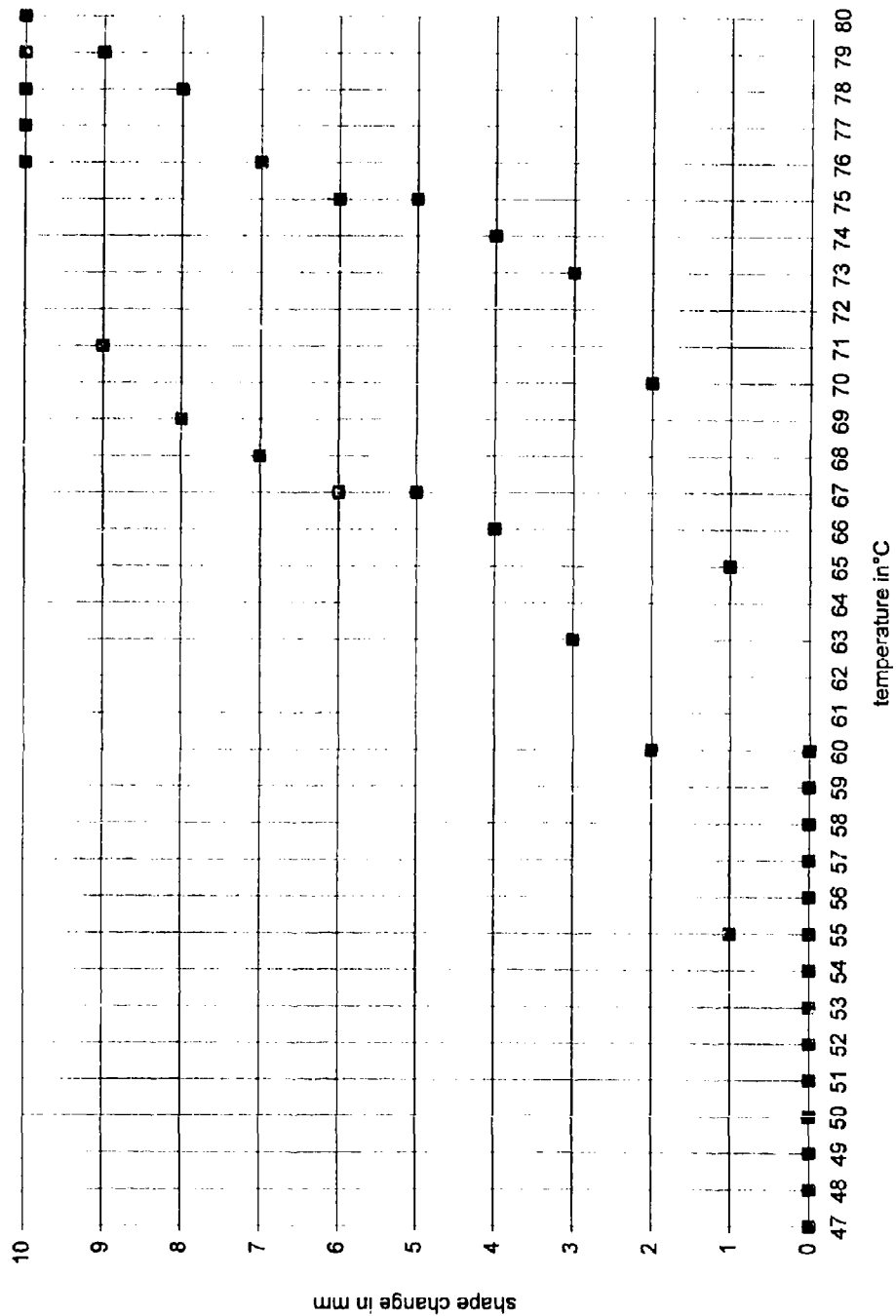
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Figure 1 Temperature-way-characteristic of CuZnAl bending element (Measurement series taken during first thermal cycle)



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Figure 2 Temperature-way-characteristic of CuZnAl bending element (Measuring during 2nd thermal cycle)



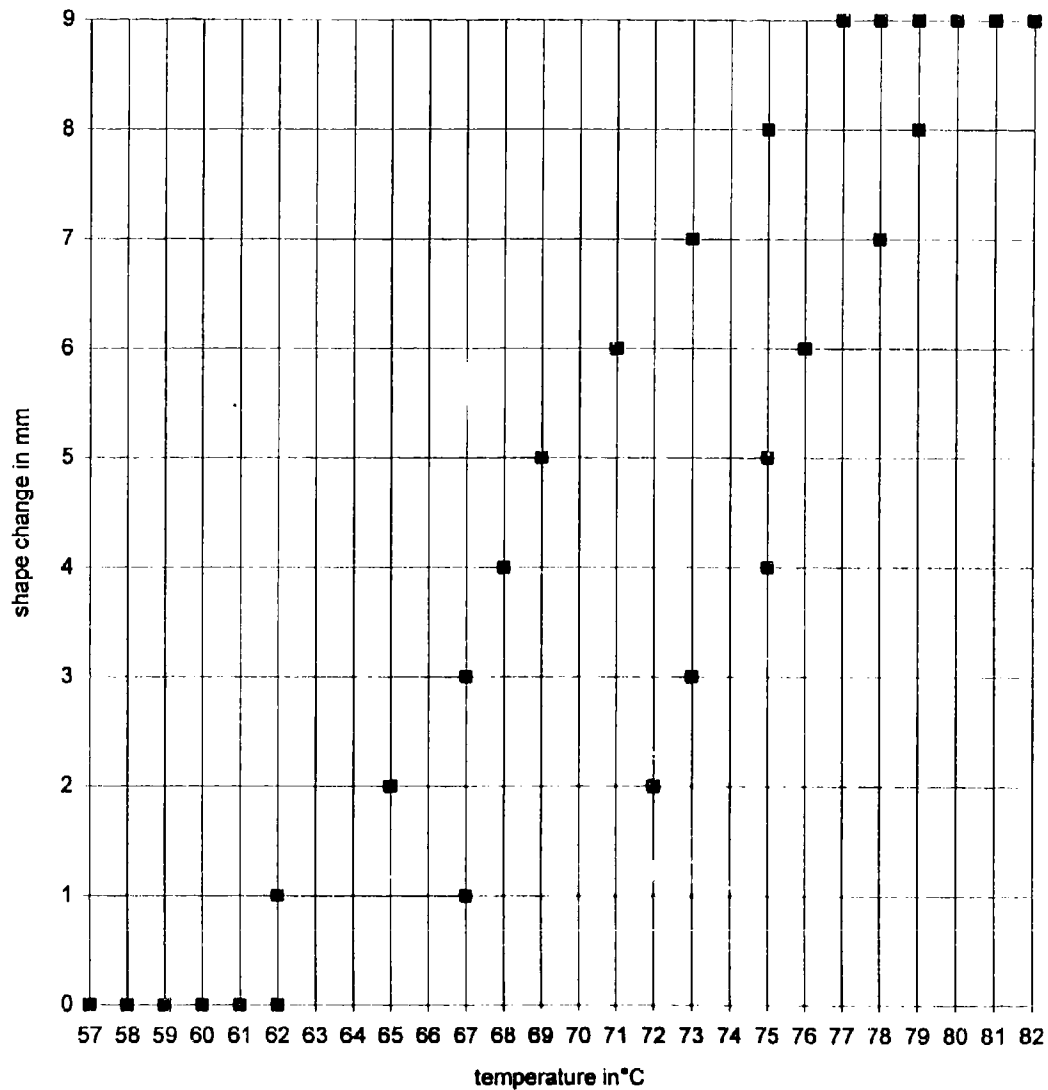
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Figure 3 Temperature-Way-characteristic of CuZnAl bending element (Measuring during 2nd thermal cycle)



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Figure 4 Temperature-Way-Characteristic of CuZnAl bending element
(Measuring during 2nd thermal cycle)

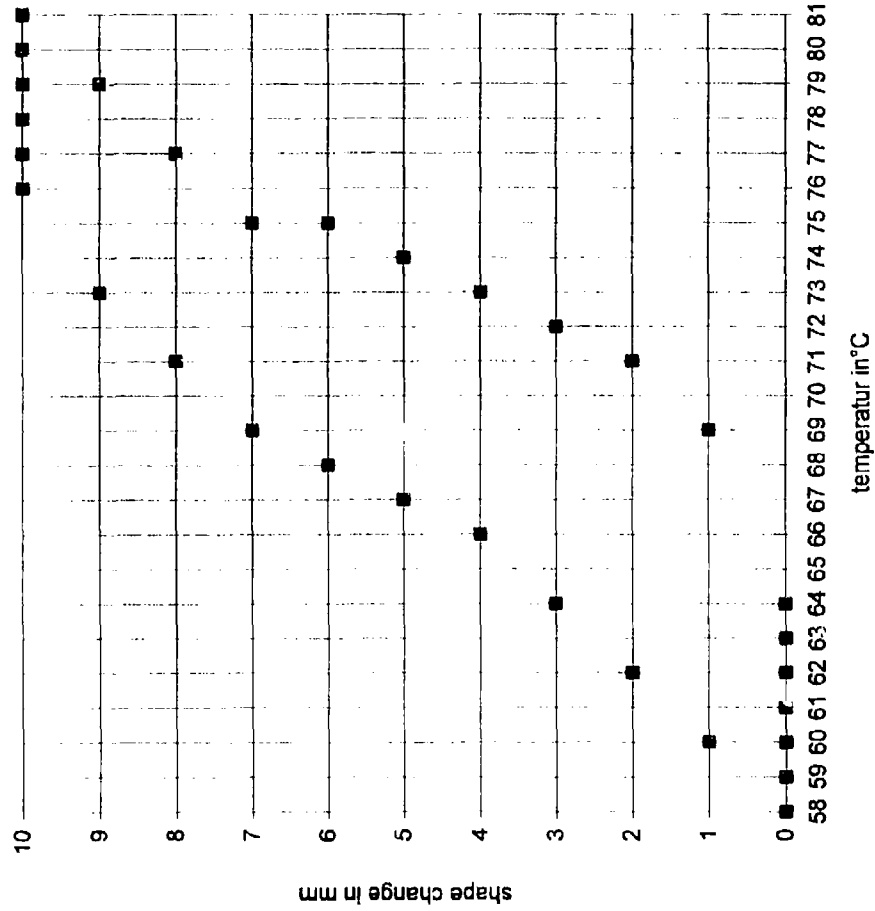


Figure 5 Temperature-Way-Characteristics of CuZnAl bending elements (comparison of figures 1 to 4)

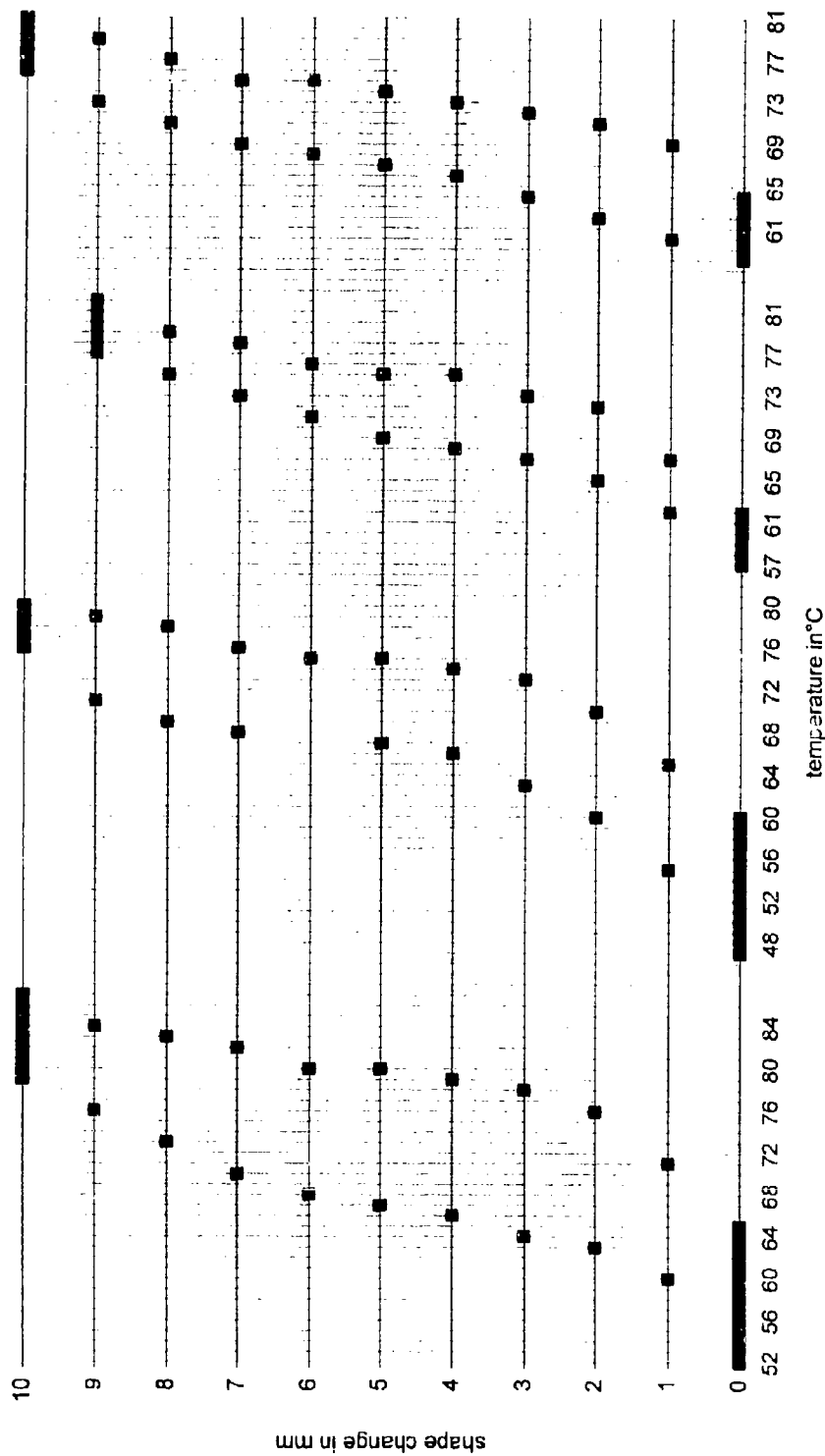
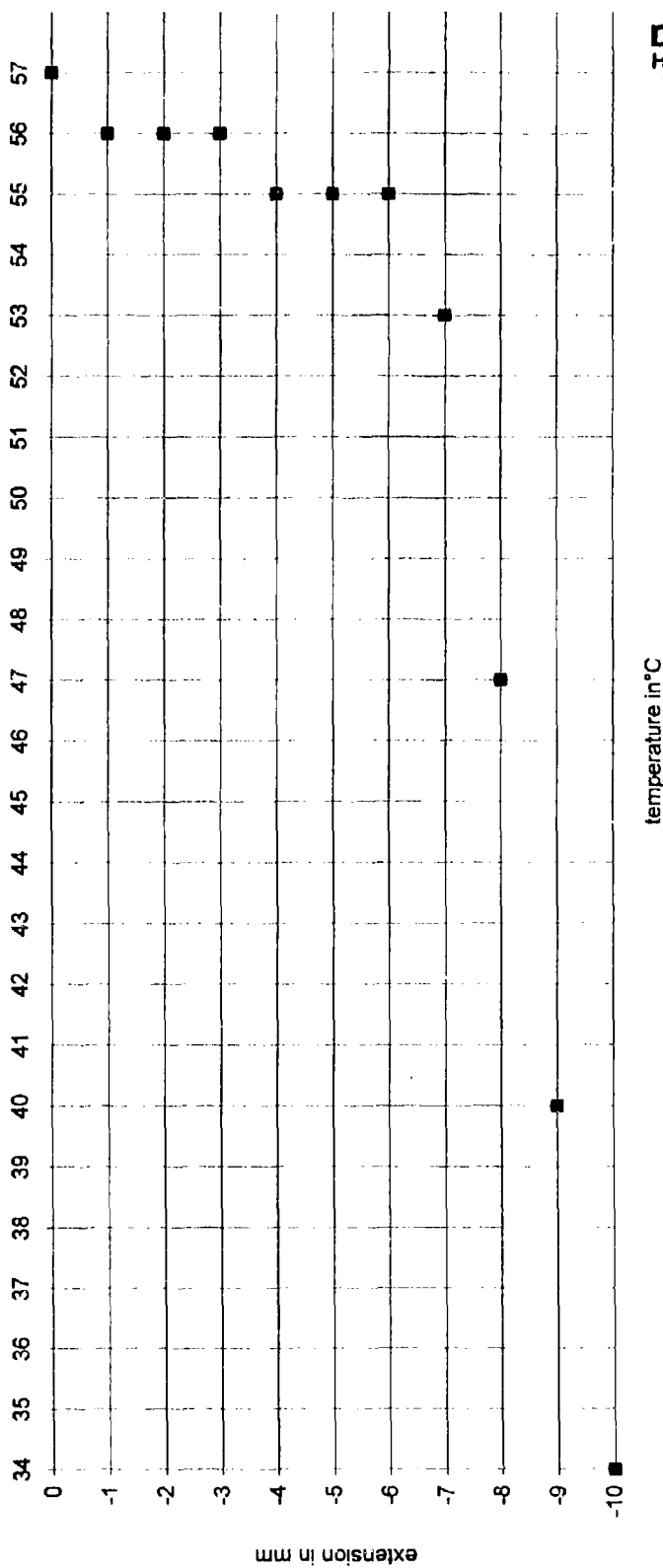
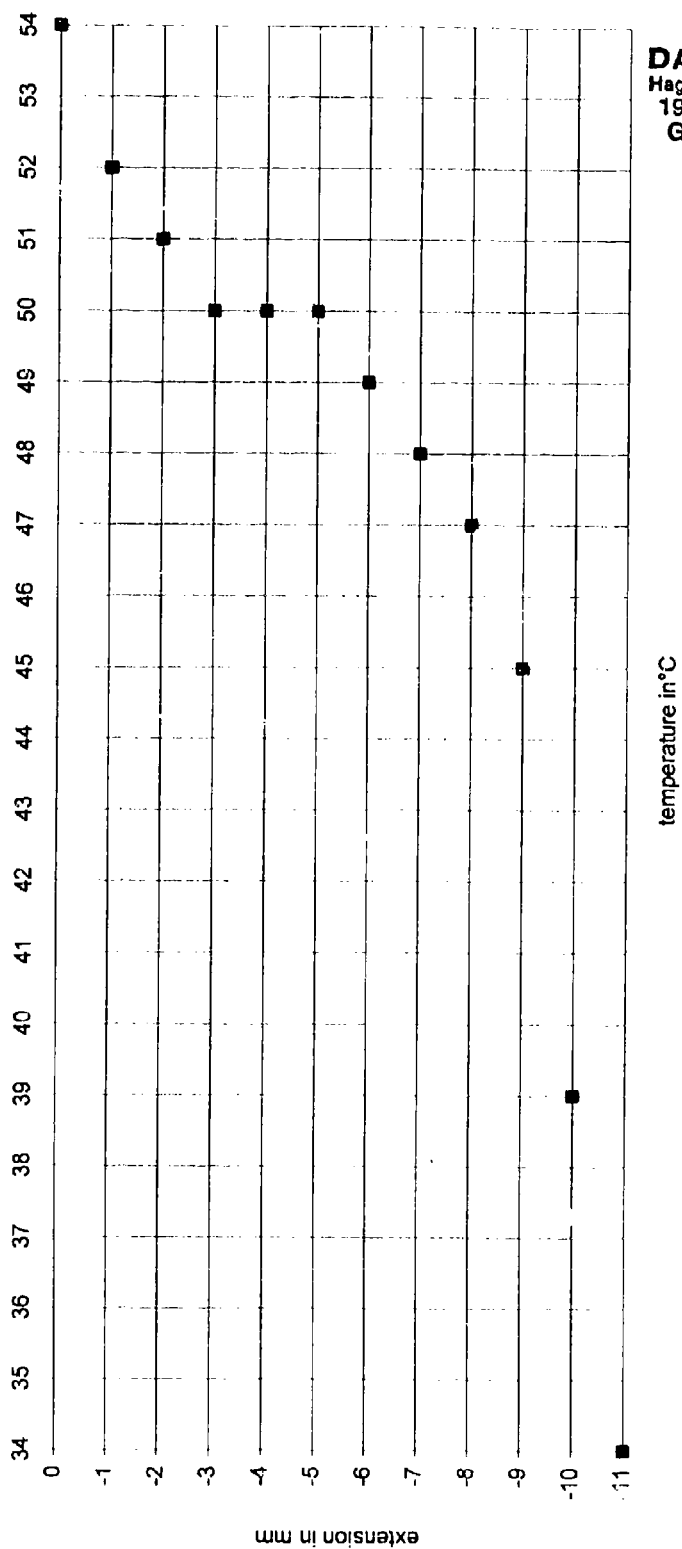


Figure 6 Temperature-Way-Characteristic of a compressed NITI compression spring



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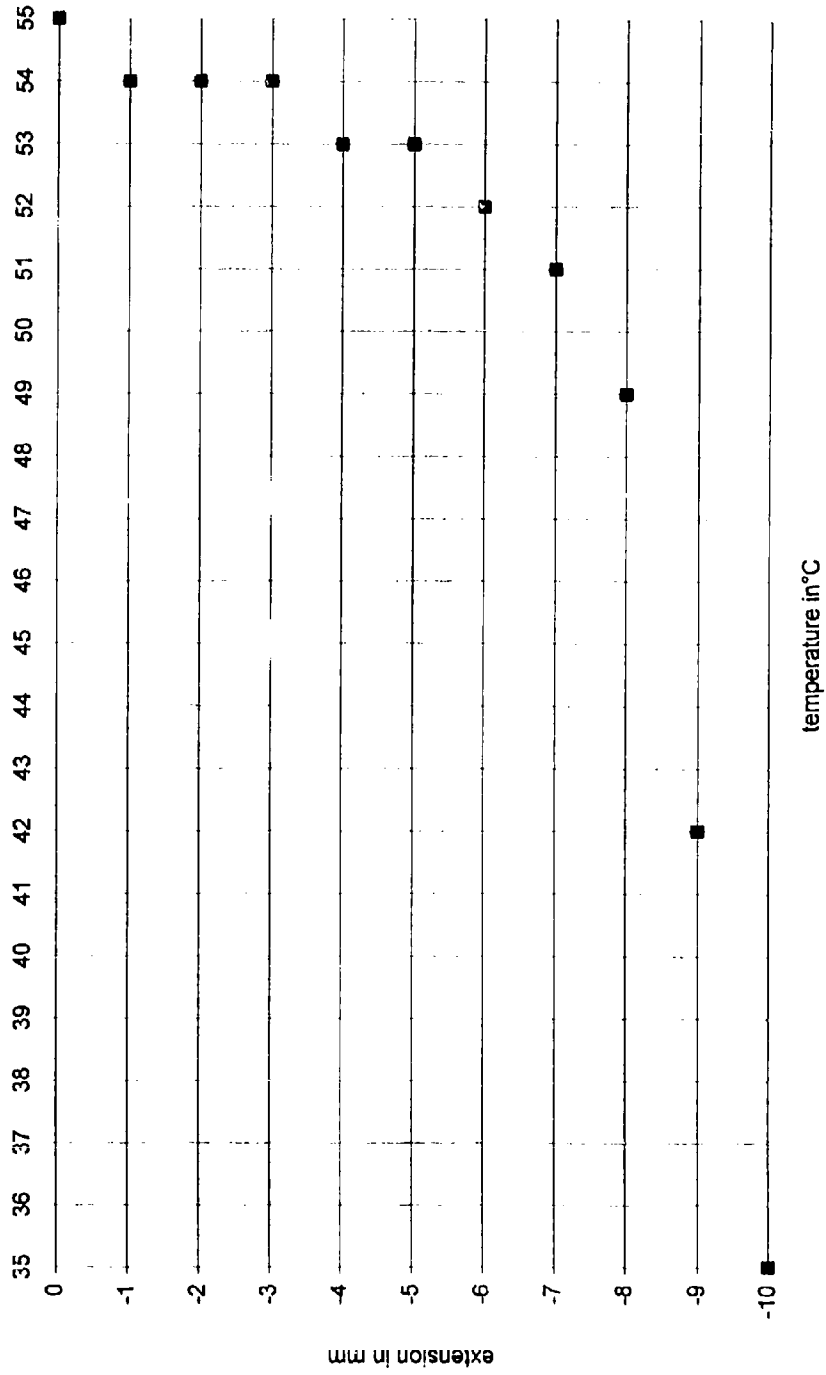
Figure 7 Temperature-Way-Characteristic of compressed NITI compression spring



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Figure 8 Temperature-Way-Characteristic of compressed NiTi compression spring



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Figure 9 Temperature-Way-Characteristic of compressed NiTi compression spring

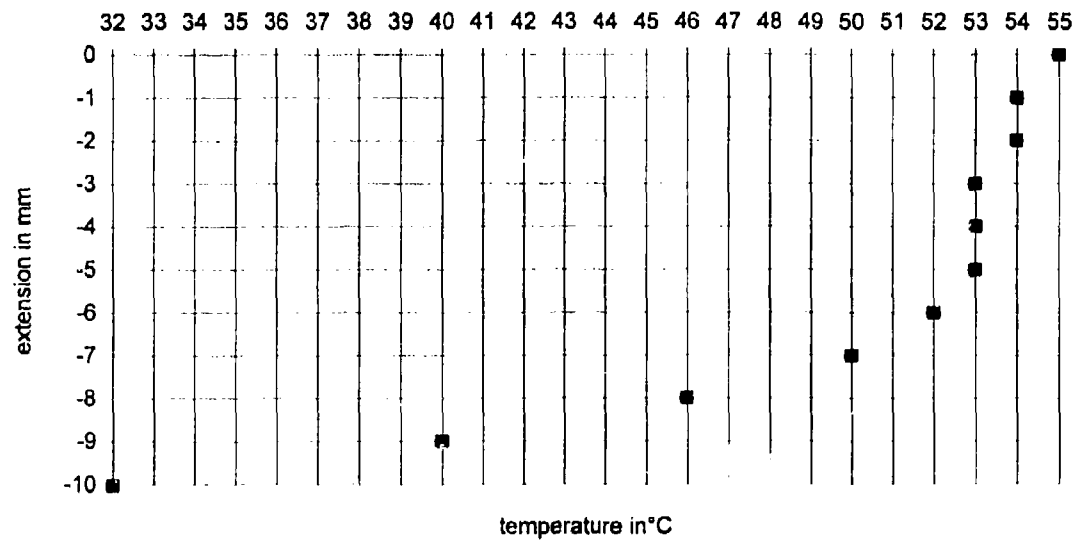


Figure 10 Temperature-Way-Characteristic of compressed NiTi compression spring (comparison, of flugre 19-22)

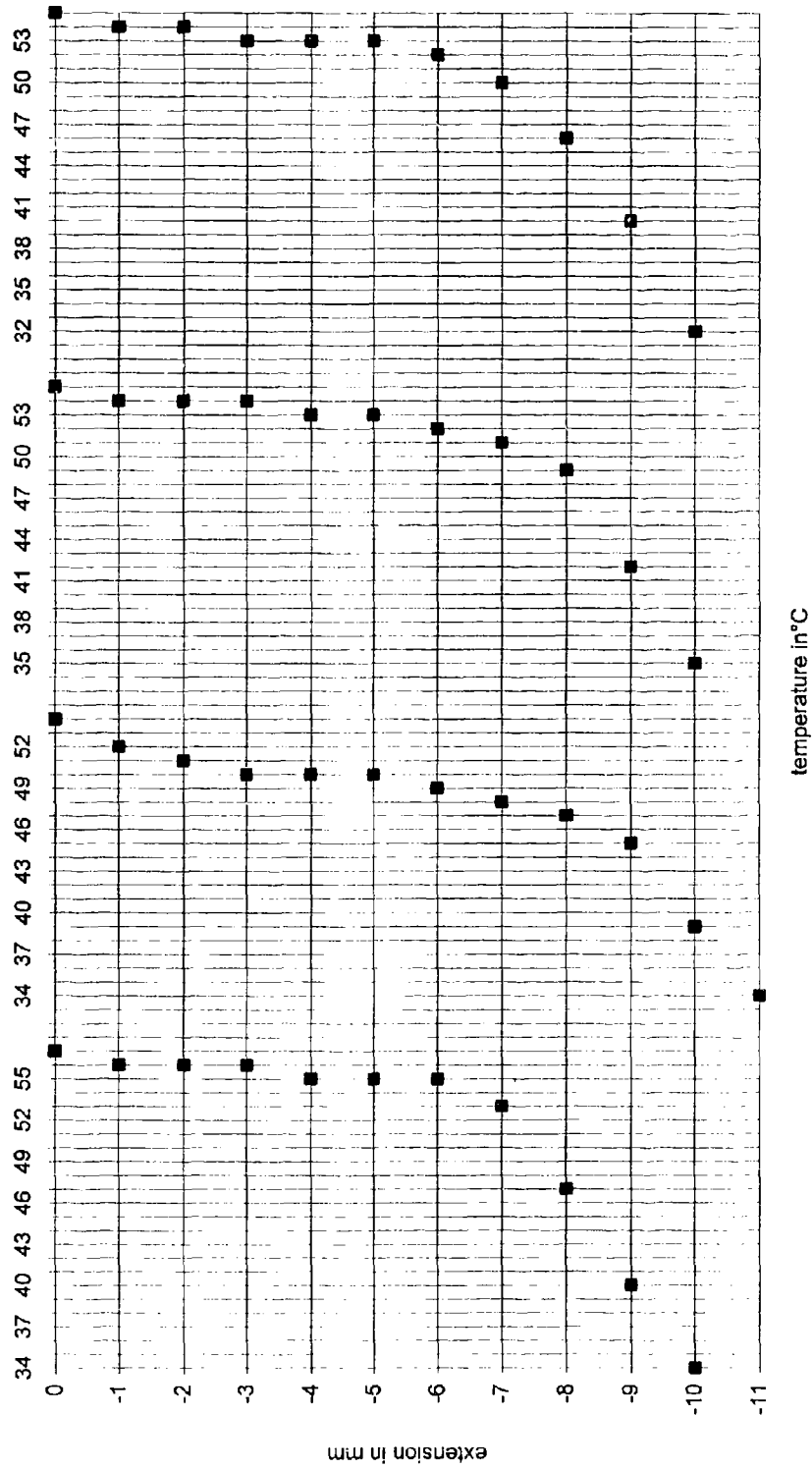
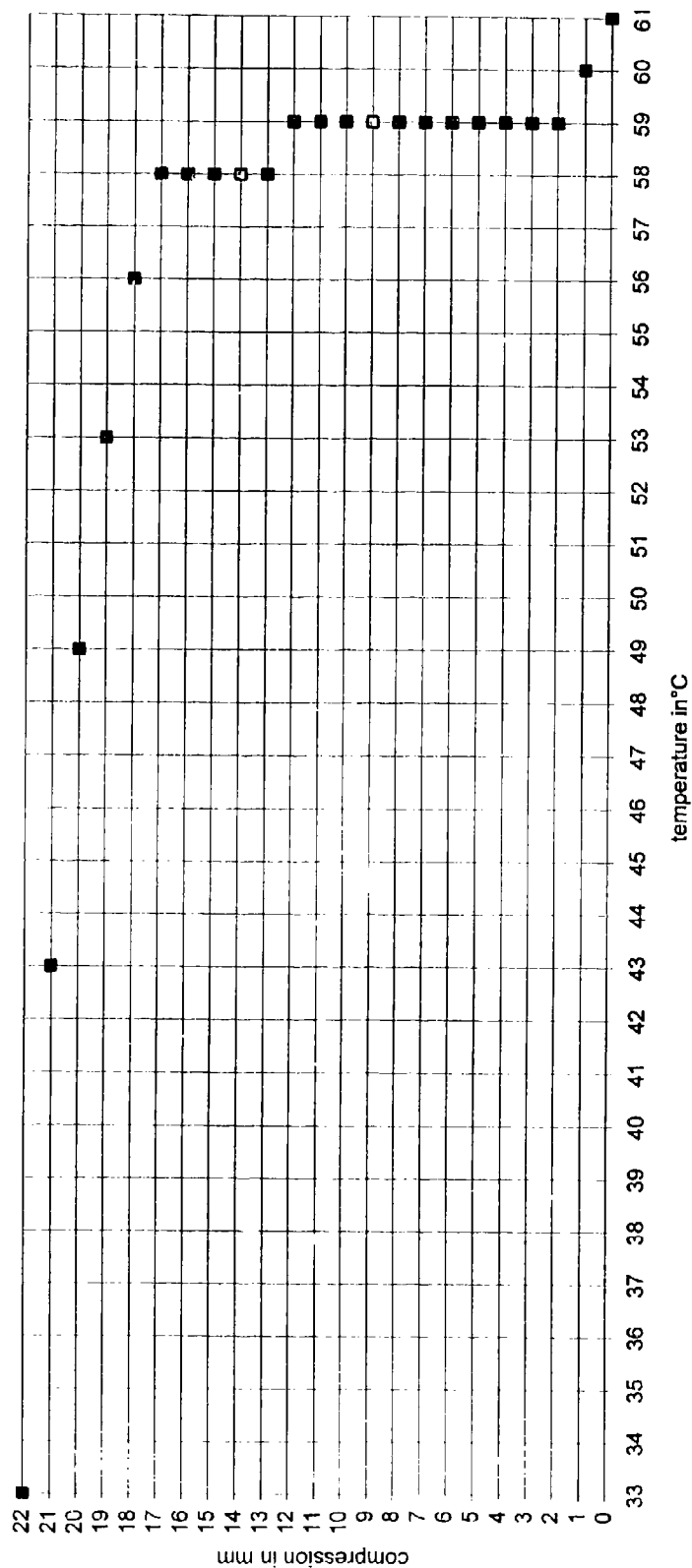


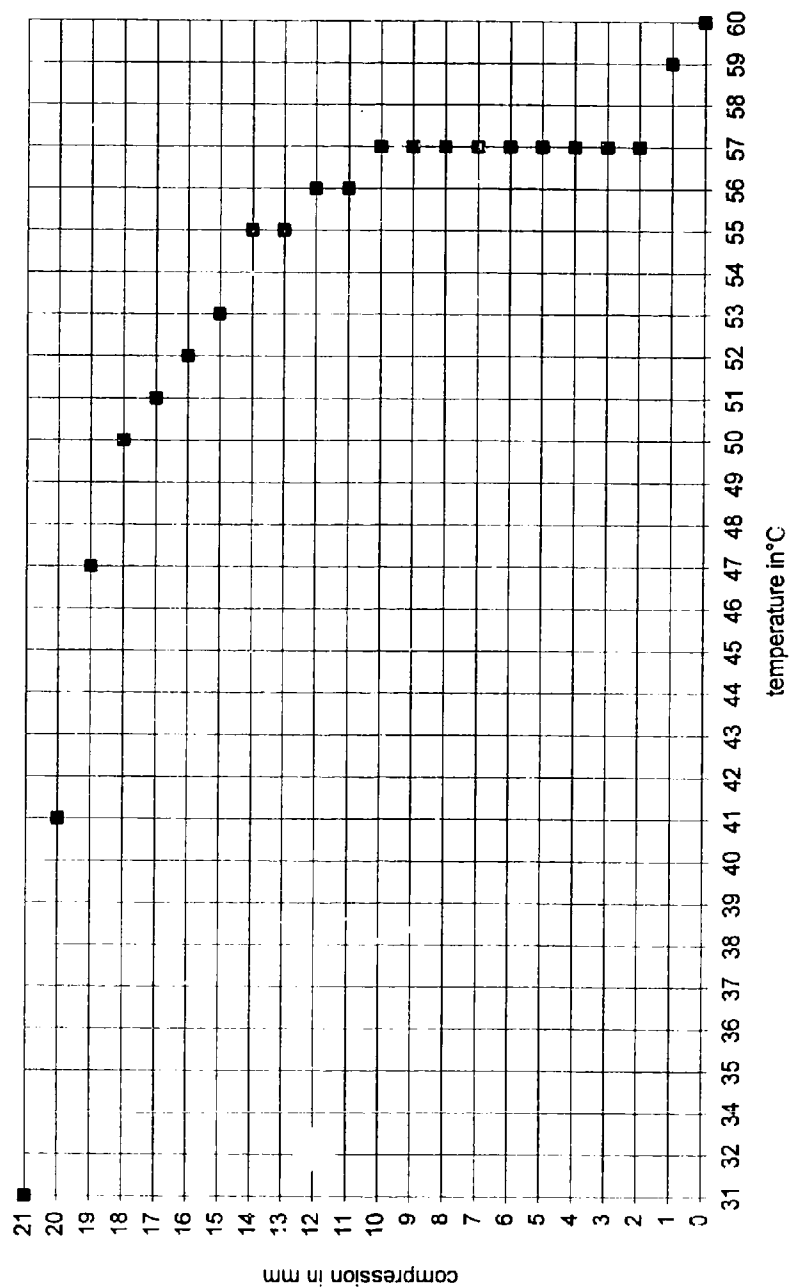
Figure 11 Temperature-Way-Characteristic of extended NITi compression spring



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Figure 12 Temperature-Way-Characteristic of an extended NITTI compression spring



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Figure 13 Temperature-Way-Characteristic of extended NITi compression spring

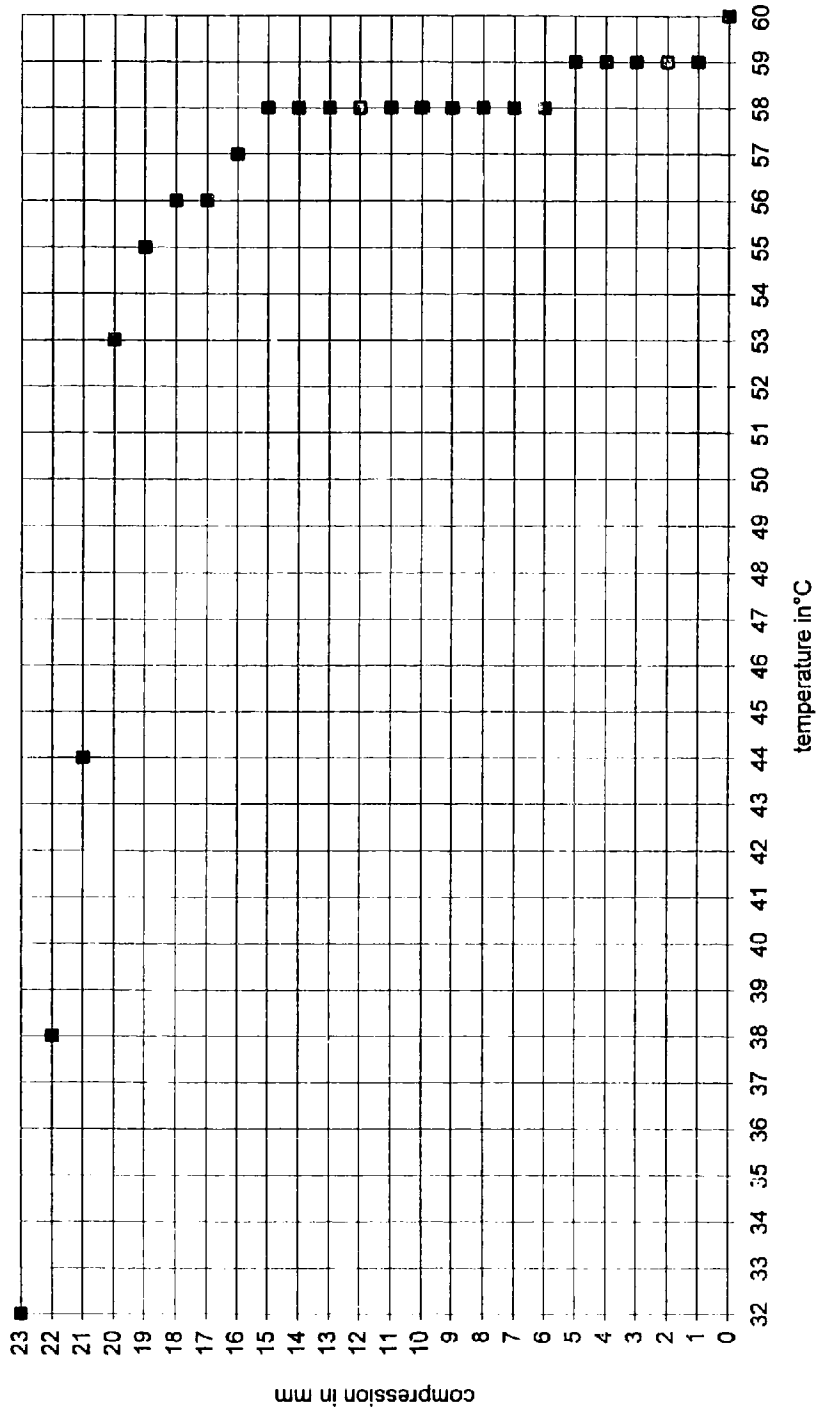


Figure 14 Temperature-Way-Characteristic of a compressed NiTi compression spring

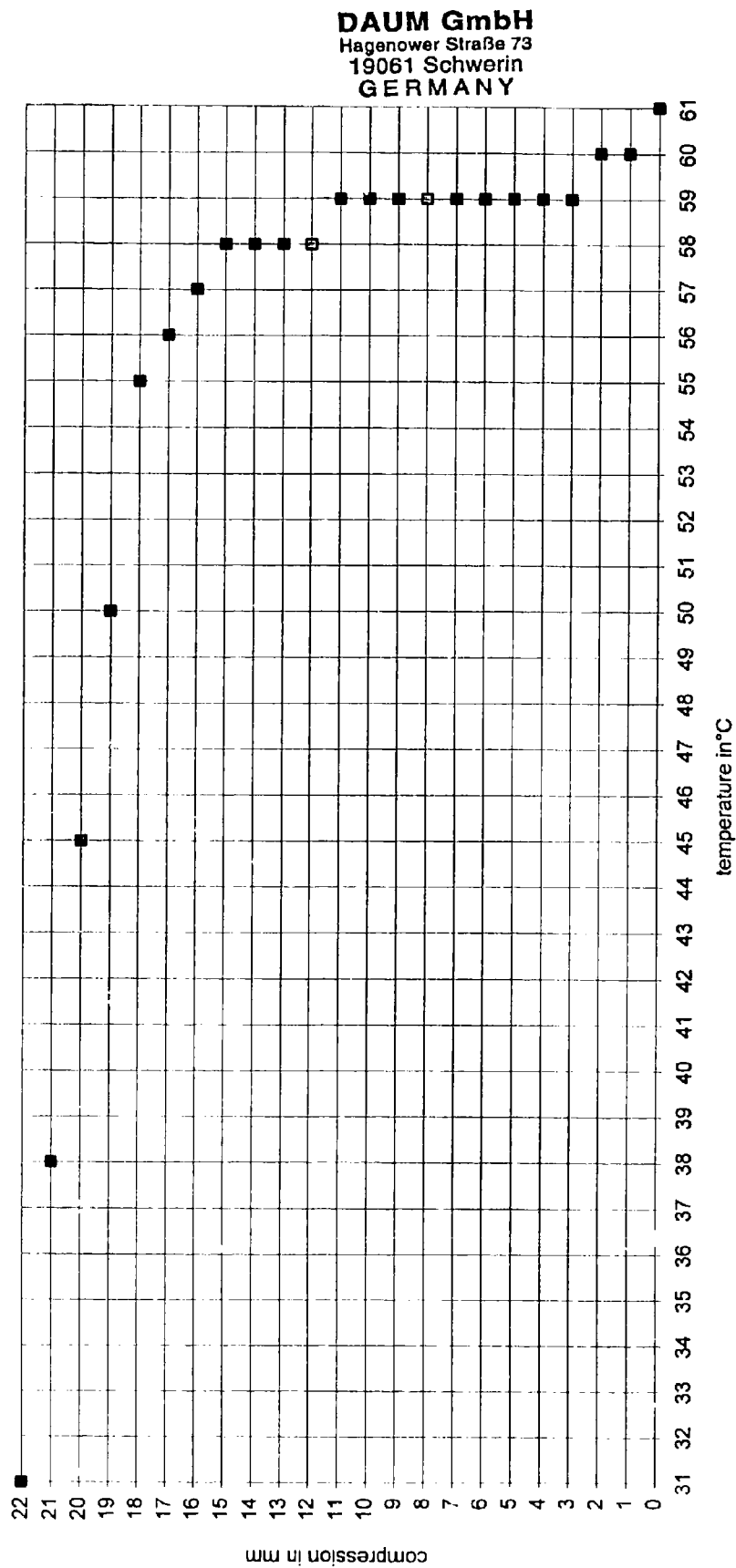
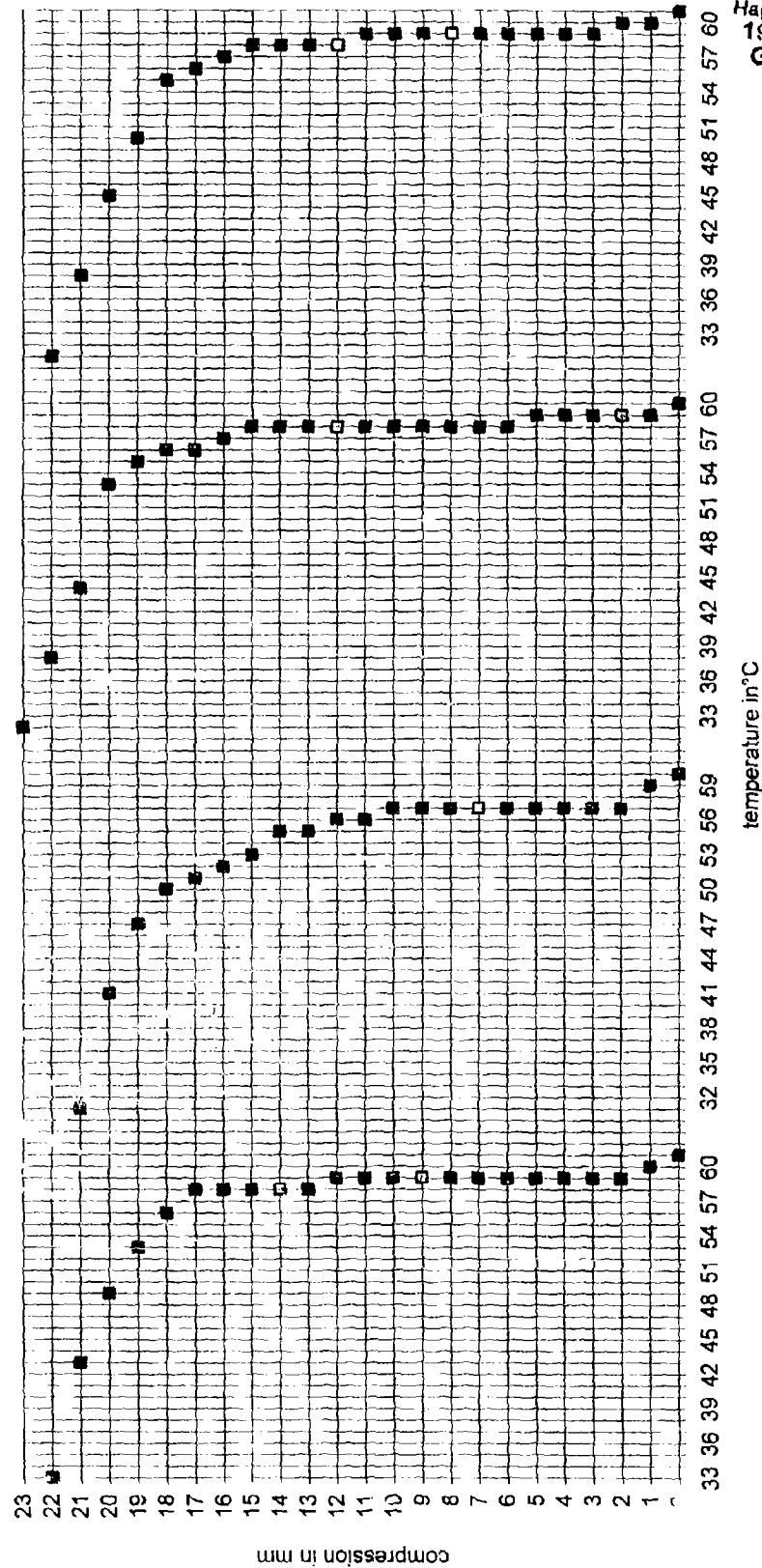


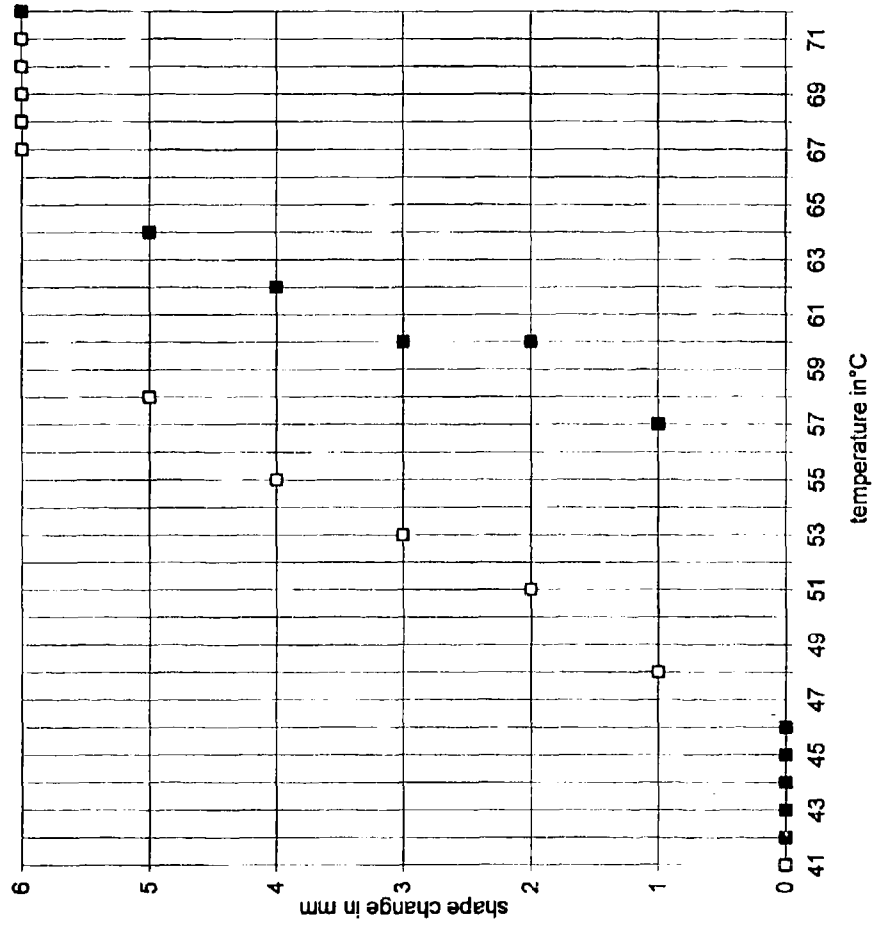
Figure 15 Temperature characteristic of compressed NiTi compression spring (Comparison of figures 24-27)



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Figure 16 Temperature-Way-Characteristic of NiTi compression spring -
material is trained for a two-way shape memory (after 1st training)



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Figure 17 Temperature-Way-Characteristic of NiTi compression spring with trained 2nd way (after 2nd training)

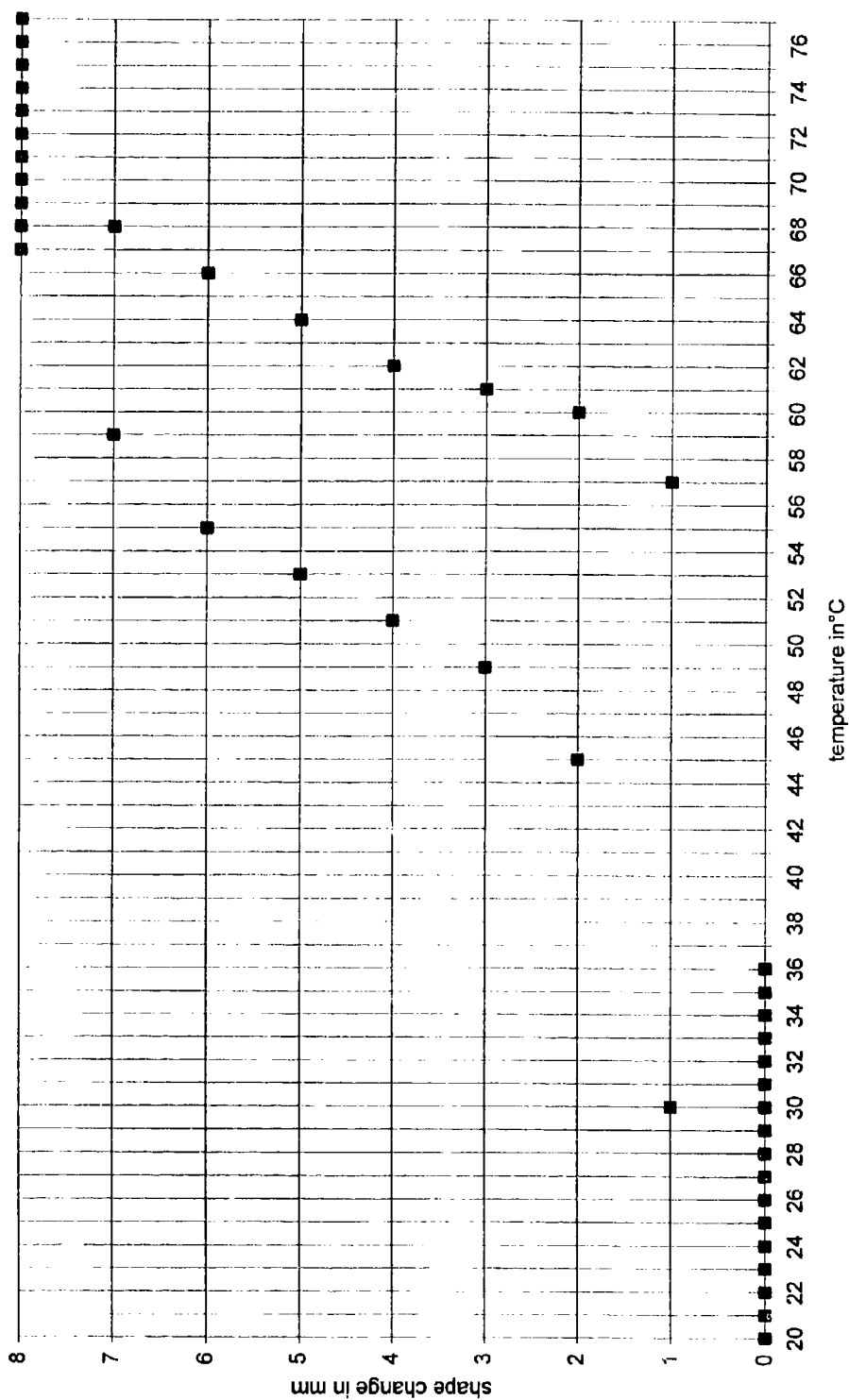


Figure 18 Temperature-Way-Characteristic of NITi compression spring with trained 2nd way (after 3rd training)

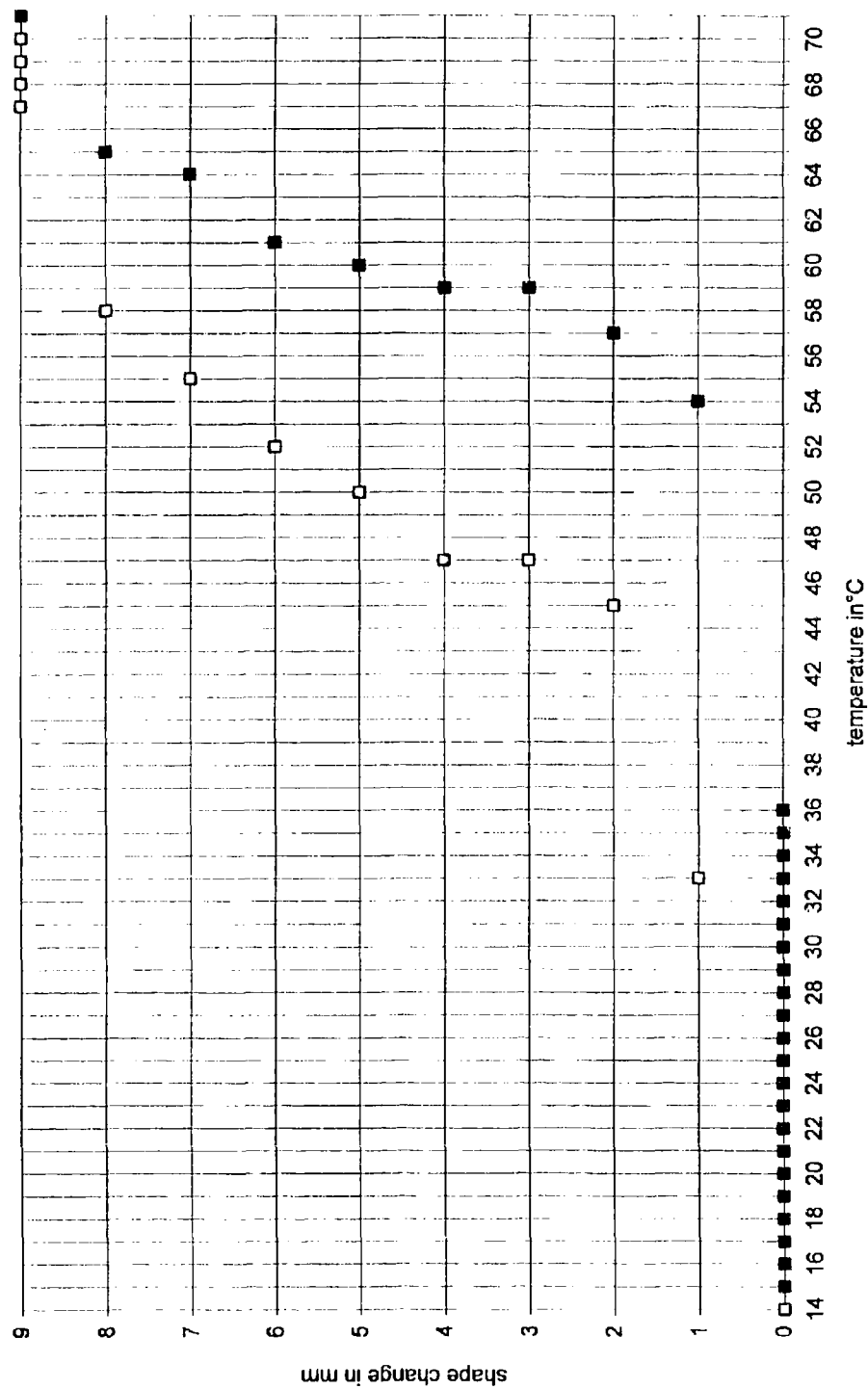


Figure 19 Temperature-Way-Characteristic of NITI compression spring with trained 2nd way (after 4th training)

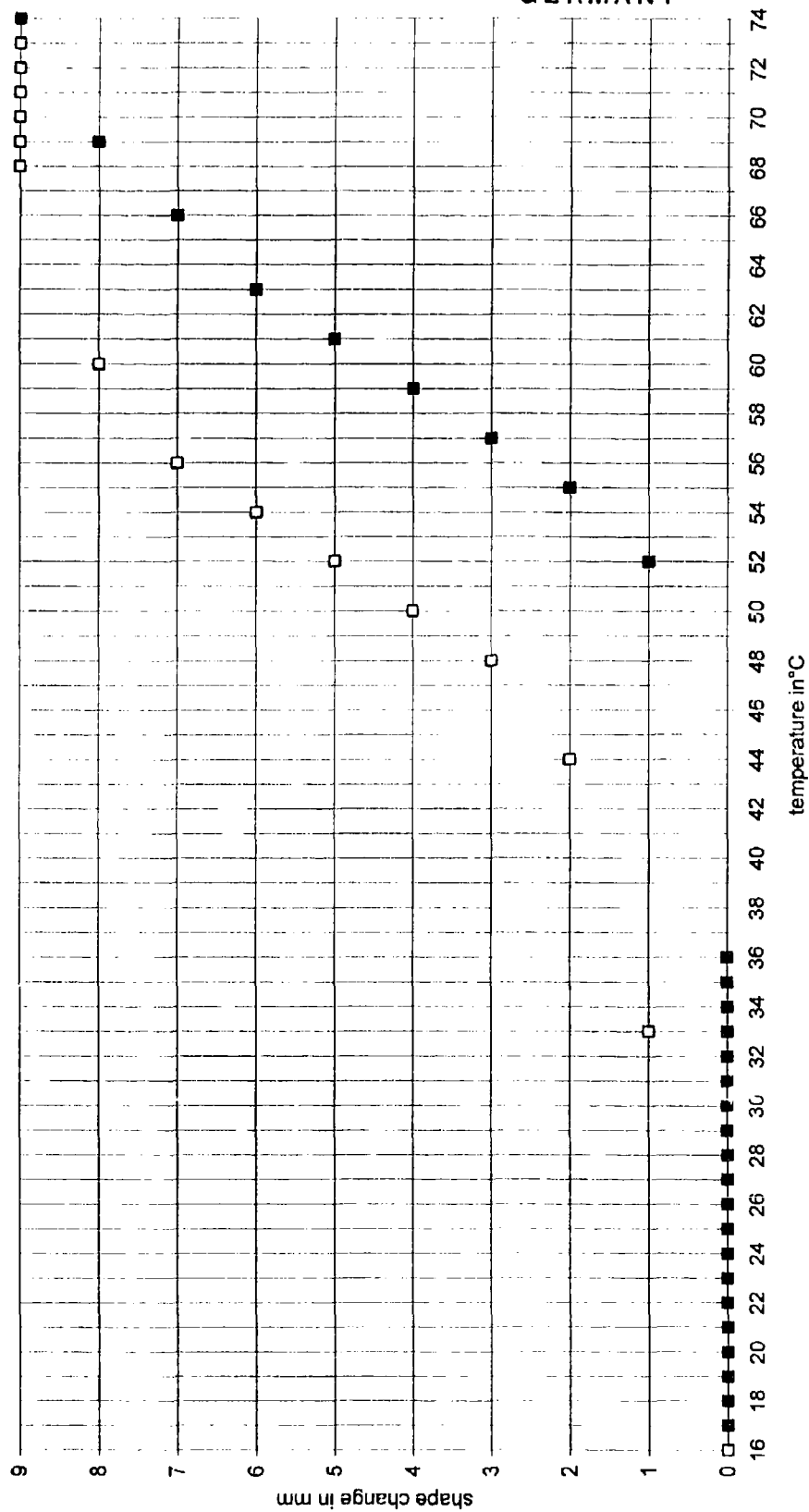
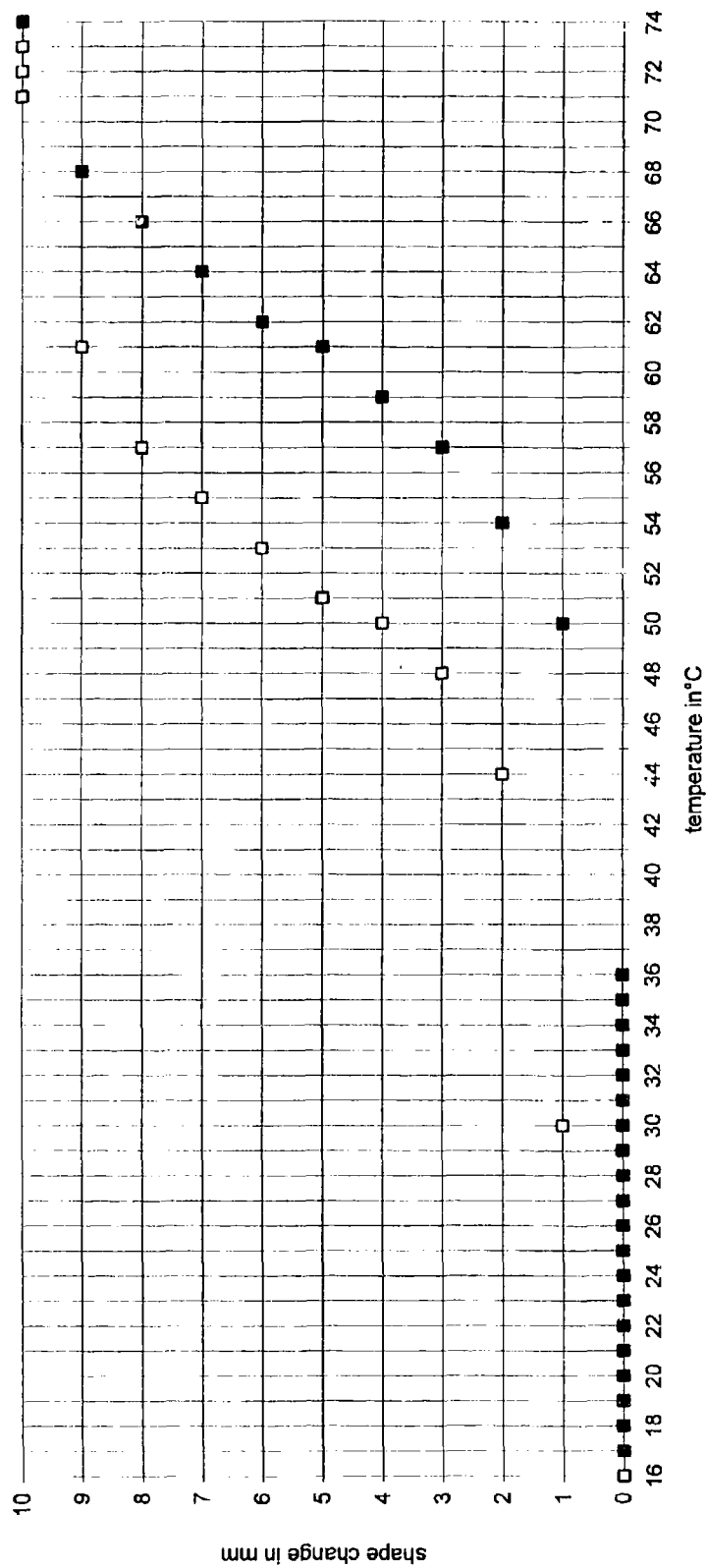
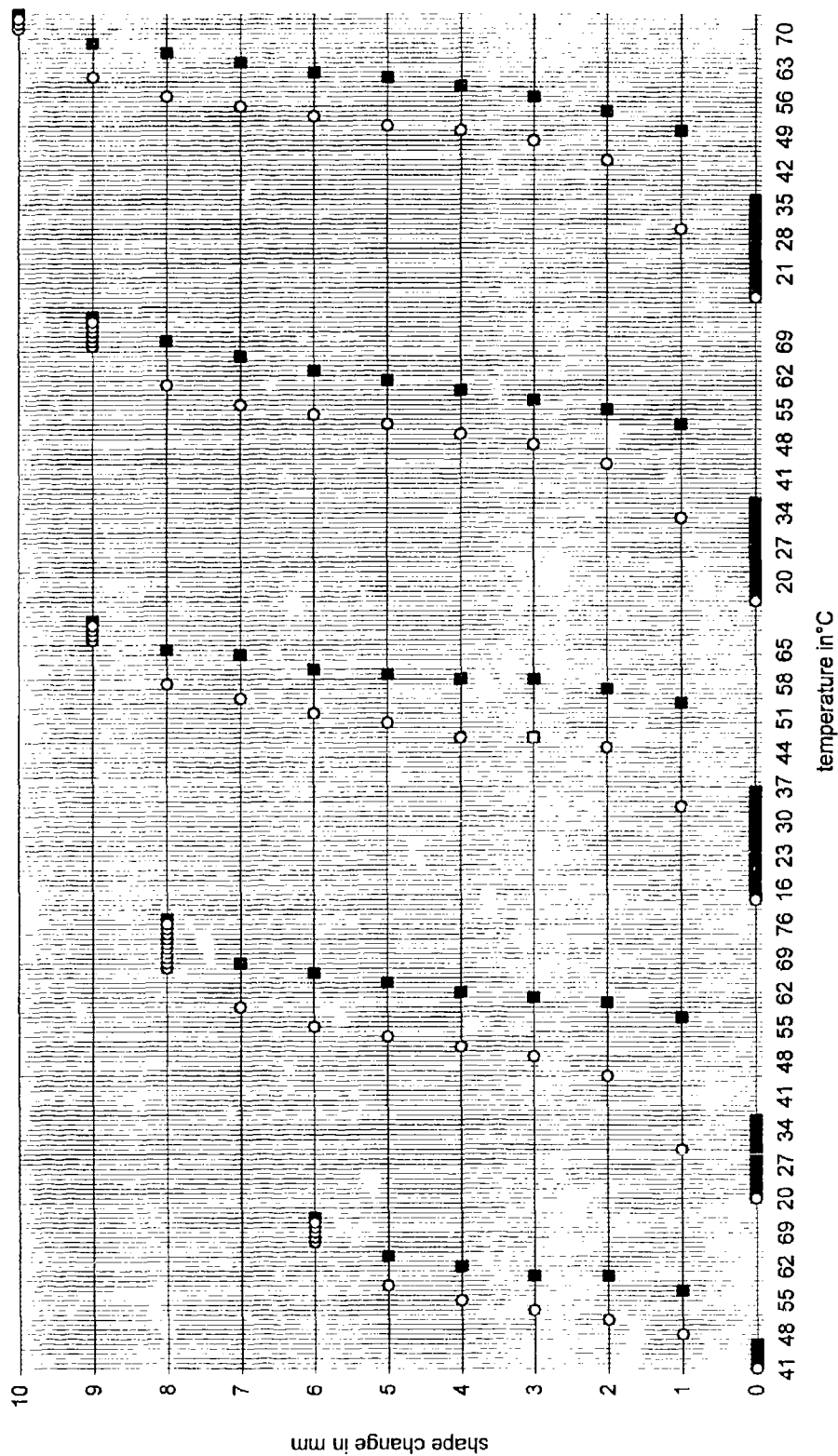


Figure 20 Temperature-Way-Characteristic of NiTi compression spring with trained 2nd way (after 5th training)

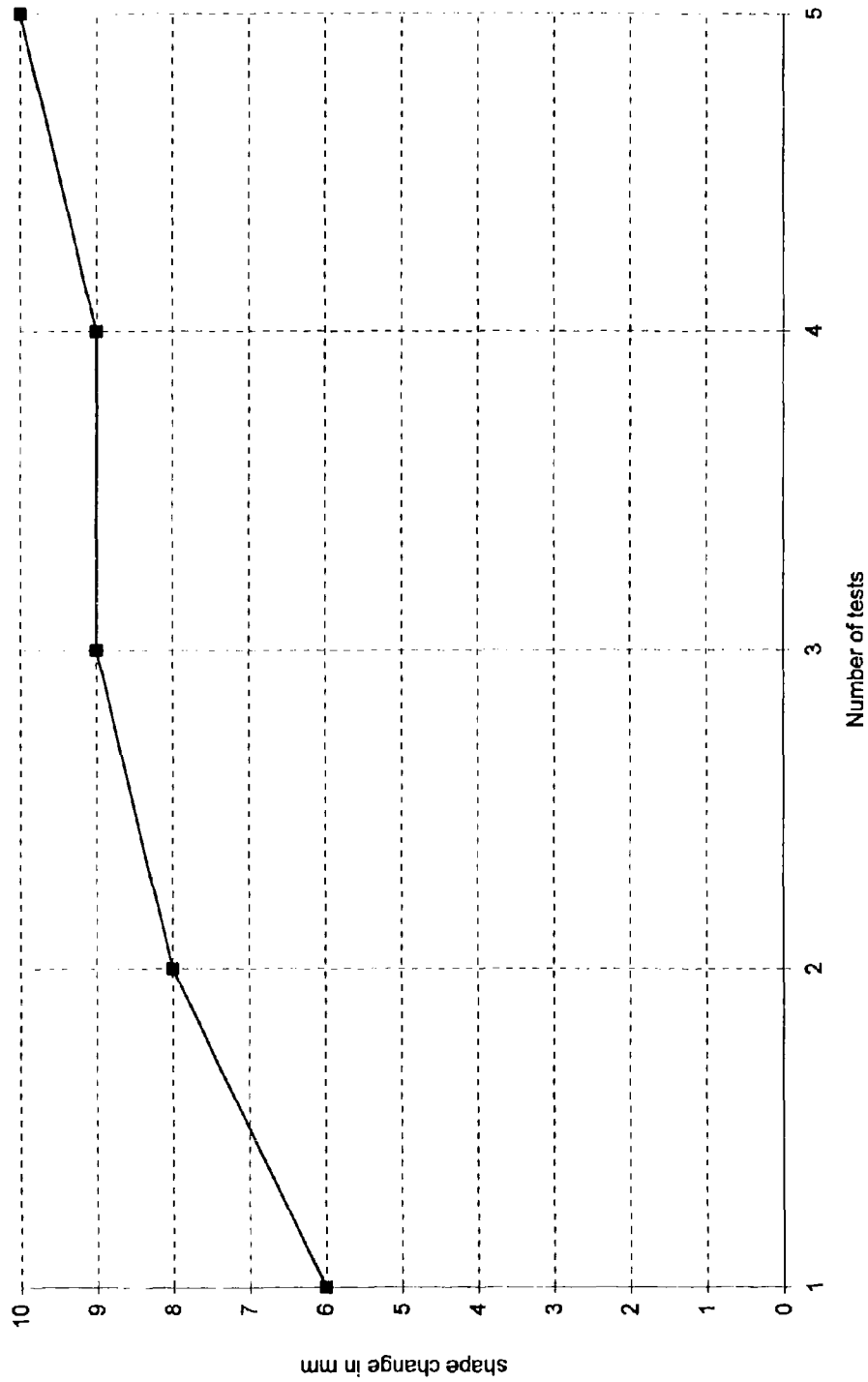


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Figure 21 Temperature-Way-Characteristic of NiTi compression spring with trained 2nd way (comparison of figures 26-33)



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Figure 22 Ability of NiTi-compression spring to memorize the second way



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Figure 23a

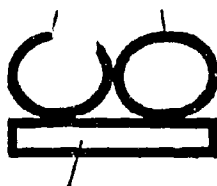


Figure 23b

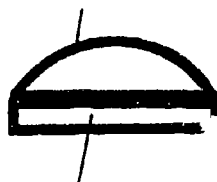


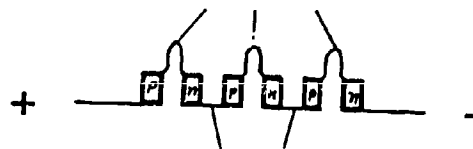
Figure 23c



Figure
23d,e



Figure 23f



construction of finger

Segment 1 Segment 2 Segment 3 Segment 4

SME	SME	SME	SME
conducting rubber	conducting rubber	conducting rubber	conducting rubber
SME	SME	SME	SME
conducting rubber	conducting rubber	conducting rubber	conducting rubber
SME	SME	SME	SME

direction of bending

NTC-Sensor

heat conducting glue

Figure 24

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principle of controlling unit

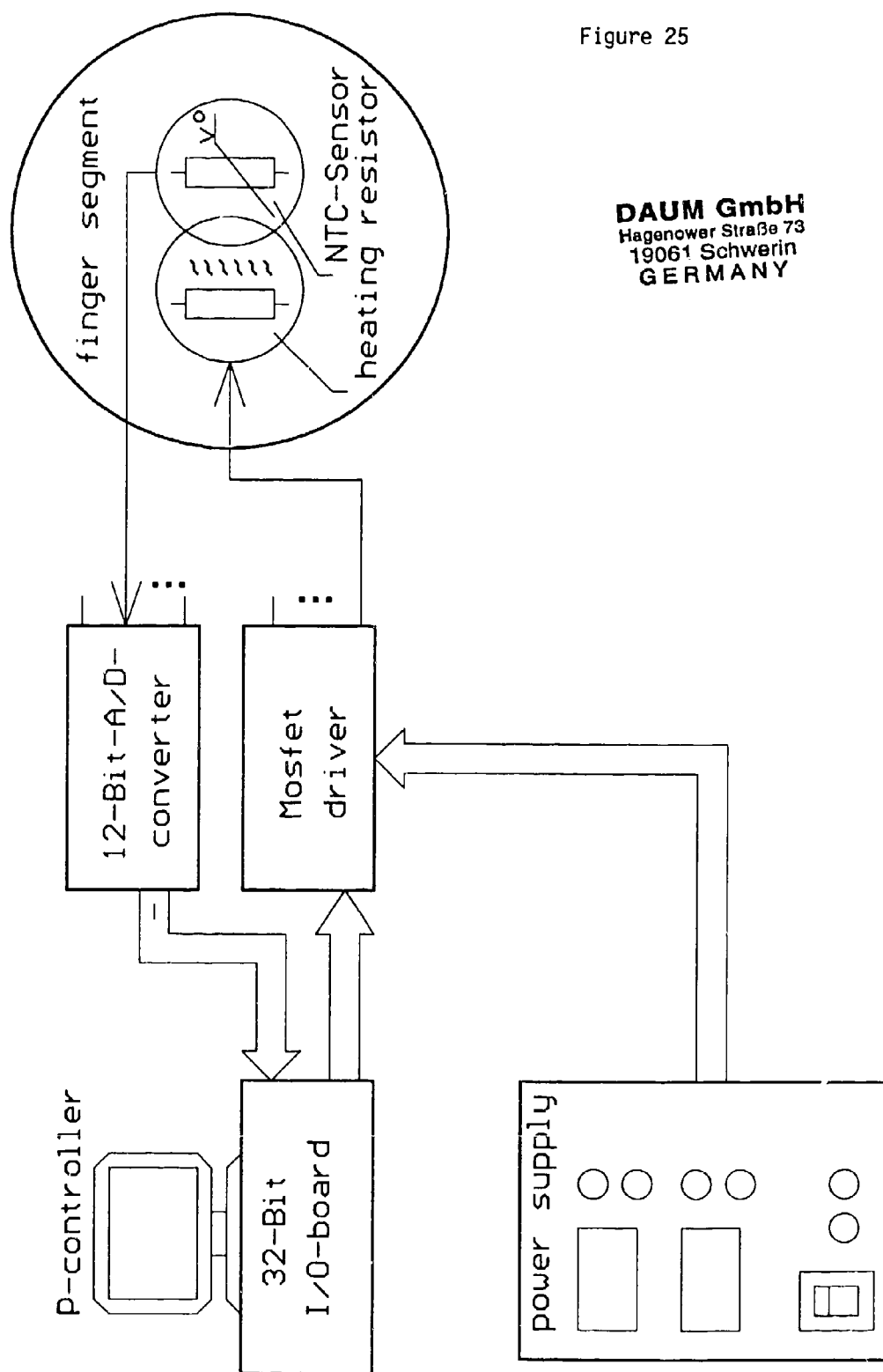


Figure 25

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pulswide as function of temperature difference

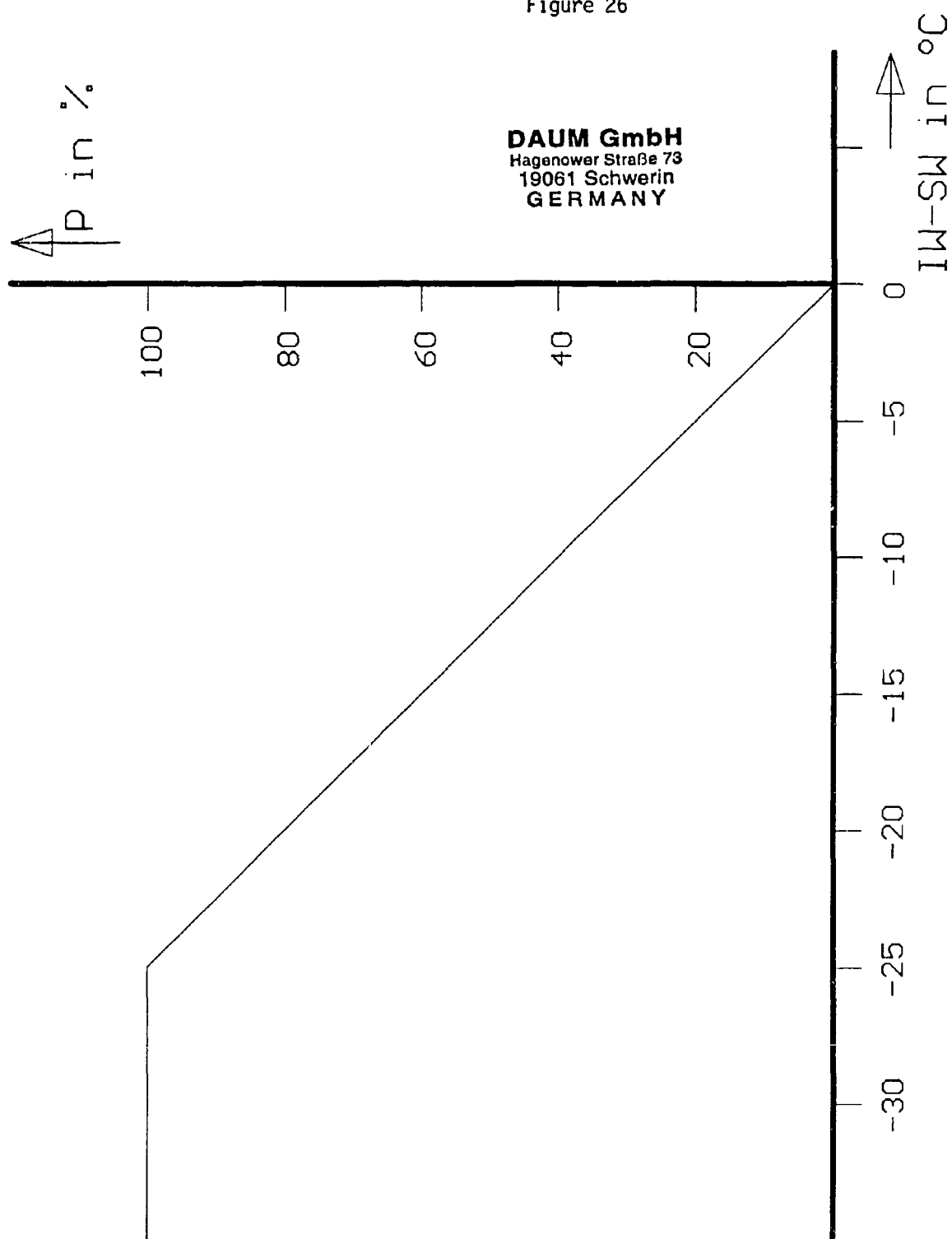
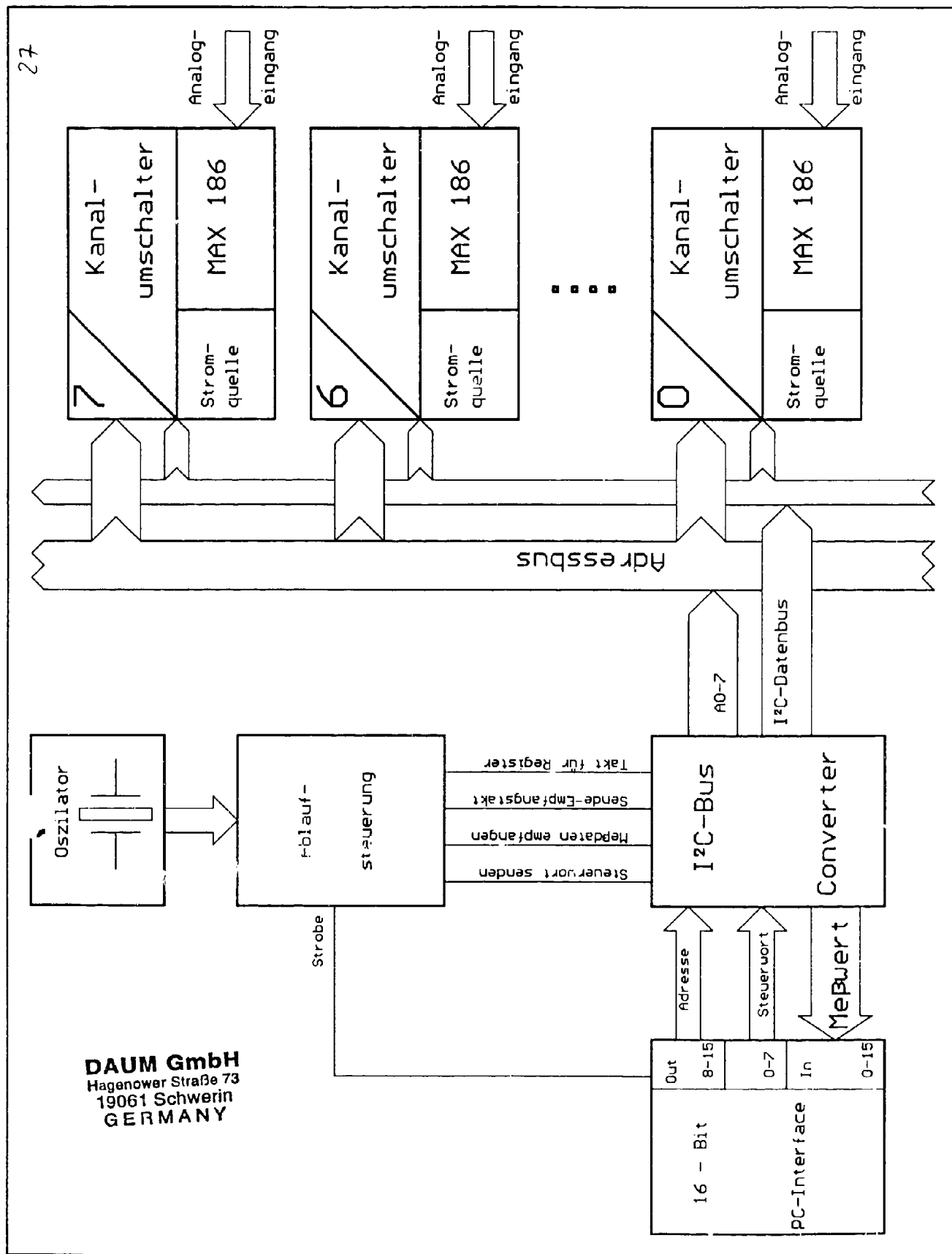


Figure 27



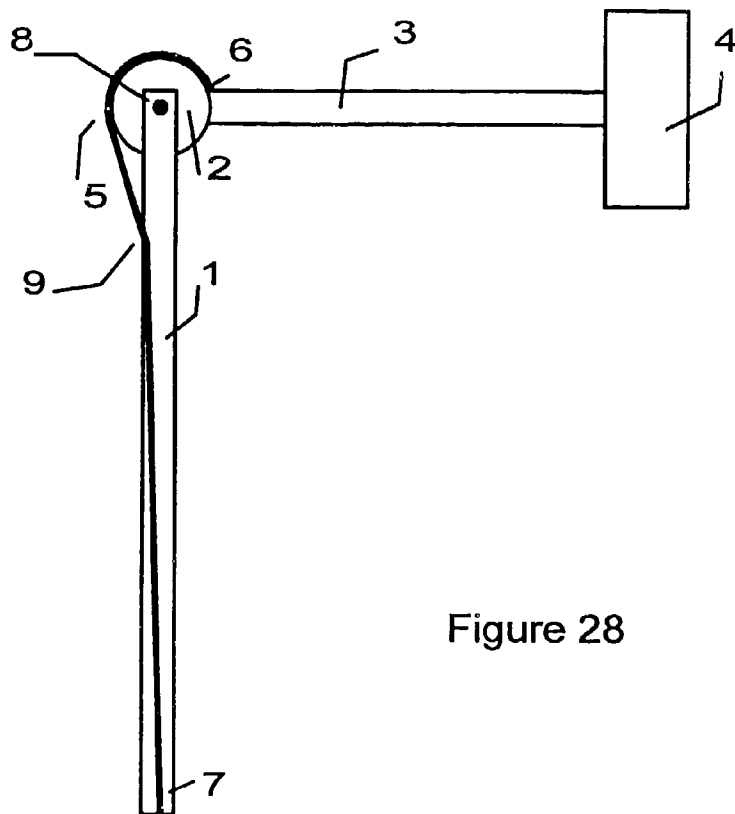
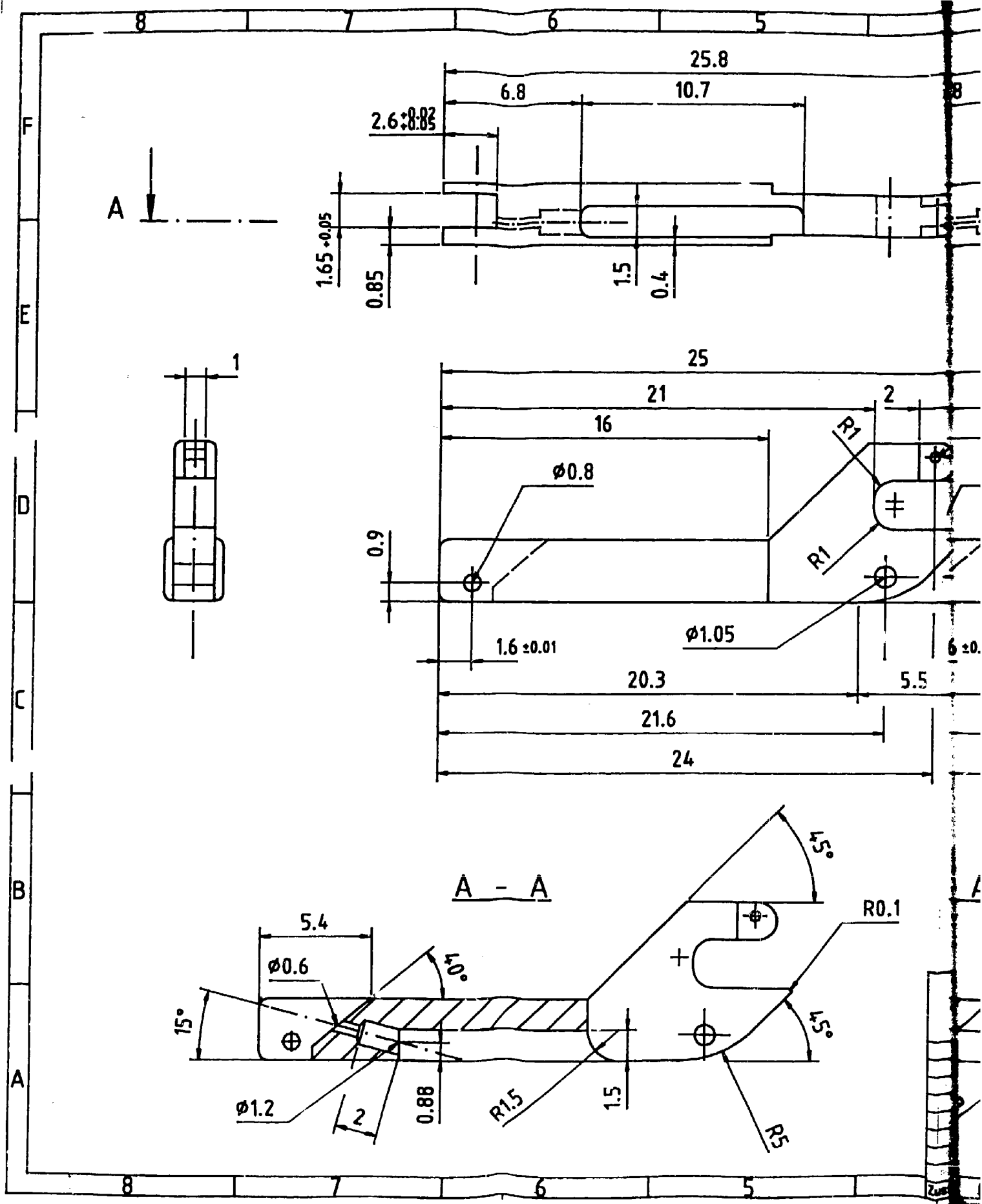
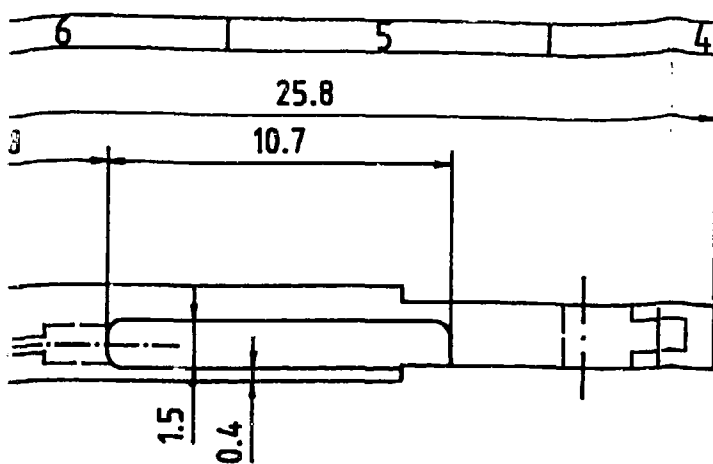


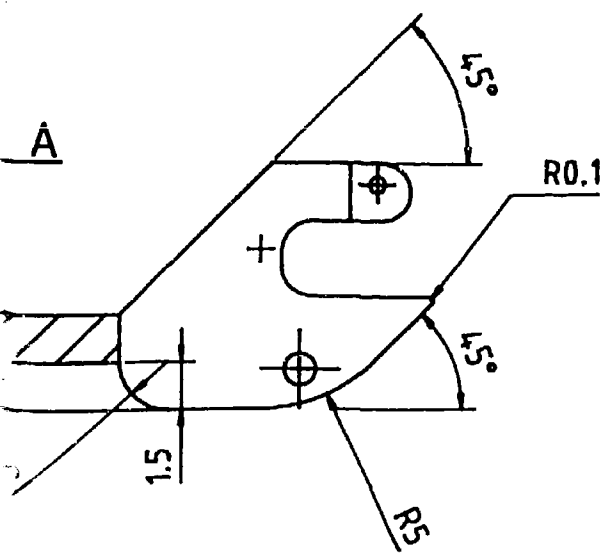
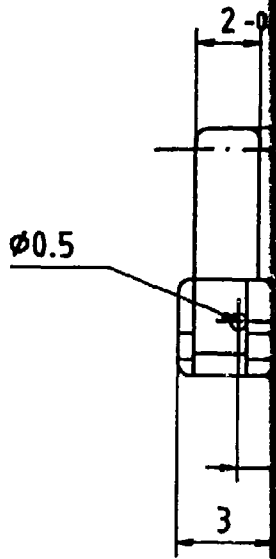
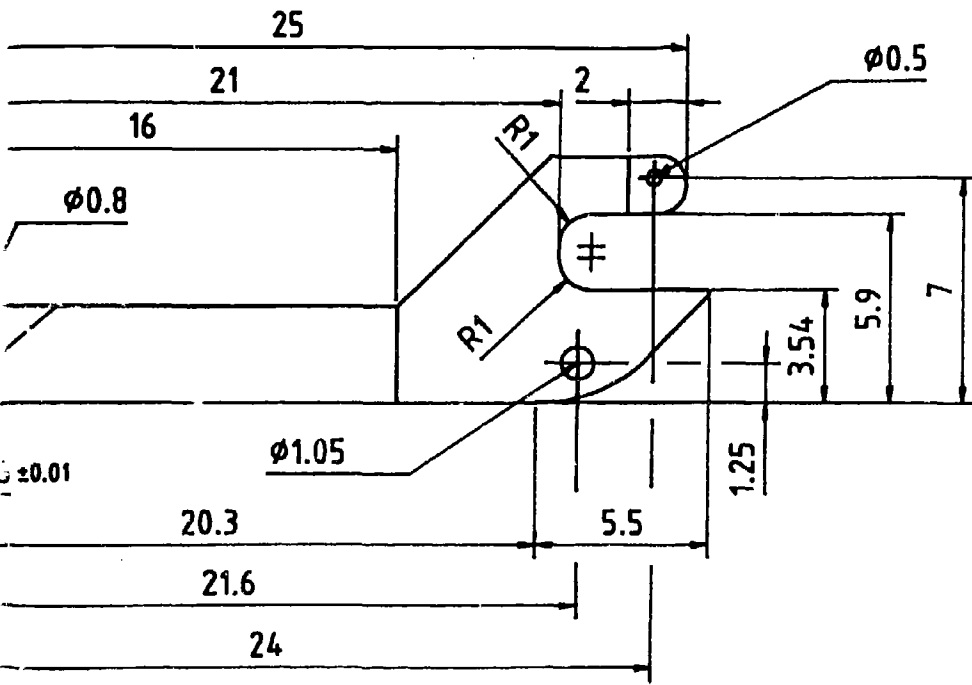
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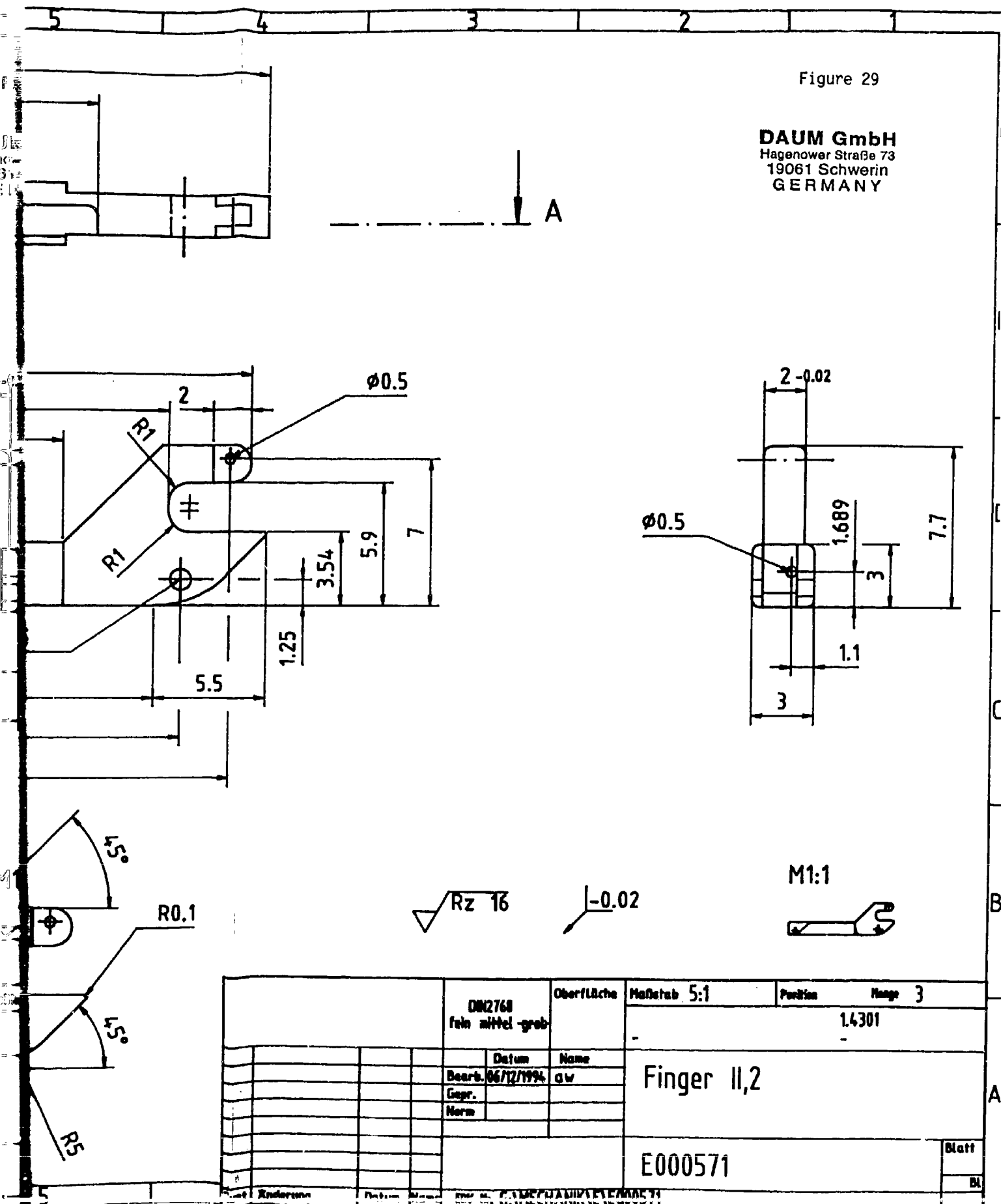
Rz 16

-0.02

				DIN2768 fein mittel-grob		Oberfläche		Maßstab 5:1		Positiv	
					Datum	Name		Finger II,2			
				Bearb.	06/12/1994	aw					
				Gepr.							
				Norm							
								E000571			
Zust.		Änderung		Datum	Name	EDV Nr. G:\MECHANIK\EXE000571					

Figure 29

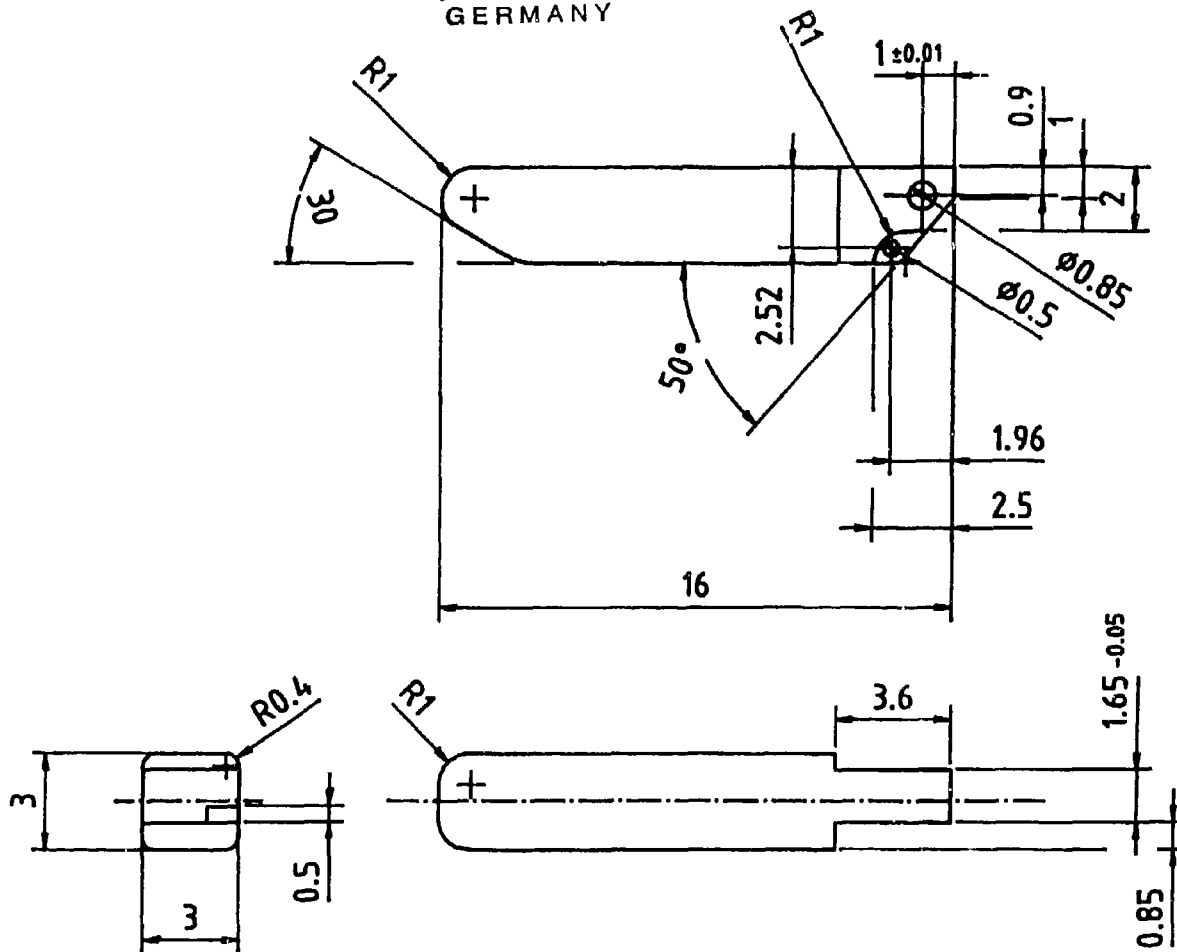
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				DN2768 fein mittel-grob	Oberfläche	Maßstab 5:1	Position	Page 3
							14301	
				Datum	Name	Finger II,2		
				Bearb. 06/12/1994	gw			
				Gepr.				
				Norm				
						E000571		
						Blatt		
						Bl		

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Figure 30



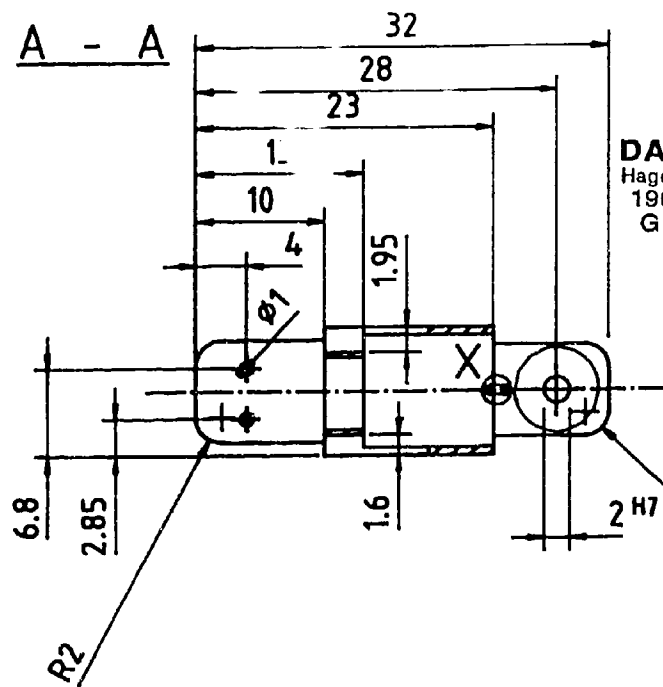
$\sqrt{Rz\ 16}$

-0.02

M1:1

				DN2768 fein mittel-grob	Oberfläche	Maßstab 5:1	Position	Page 3
							1.4301	
				Datum	Name	Finger II,1		
				Bearb. 05/12/1994	AW			
				Gepr. 26/07/1995	AW			
				Norm				
				Daum GmbH				Blatt
				E000570				Bl
Zust.	Änderung	Datum	Name	EDV Nr. C:\MECHANIK\B\B0039-01				

A - A

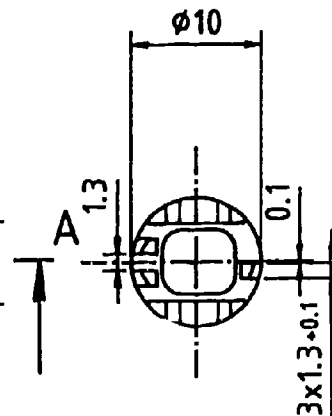
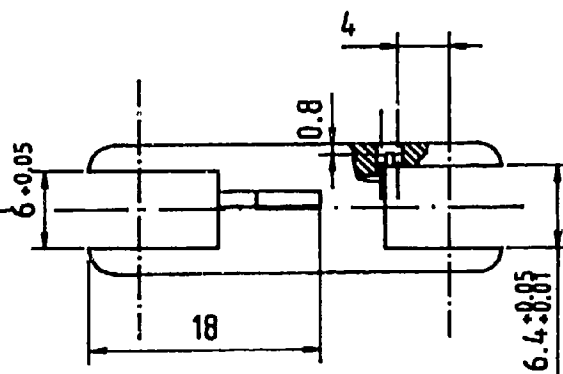
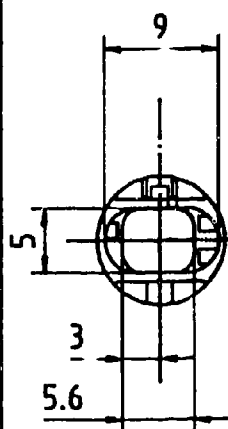
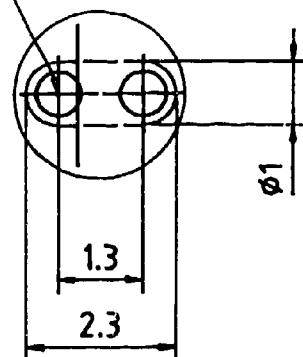


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Figure 31

Durchgangsbohrung $\phi 0.7$

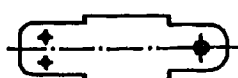
X20:1



Rz 16

-0.02

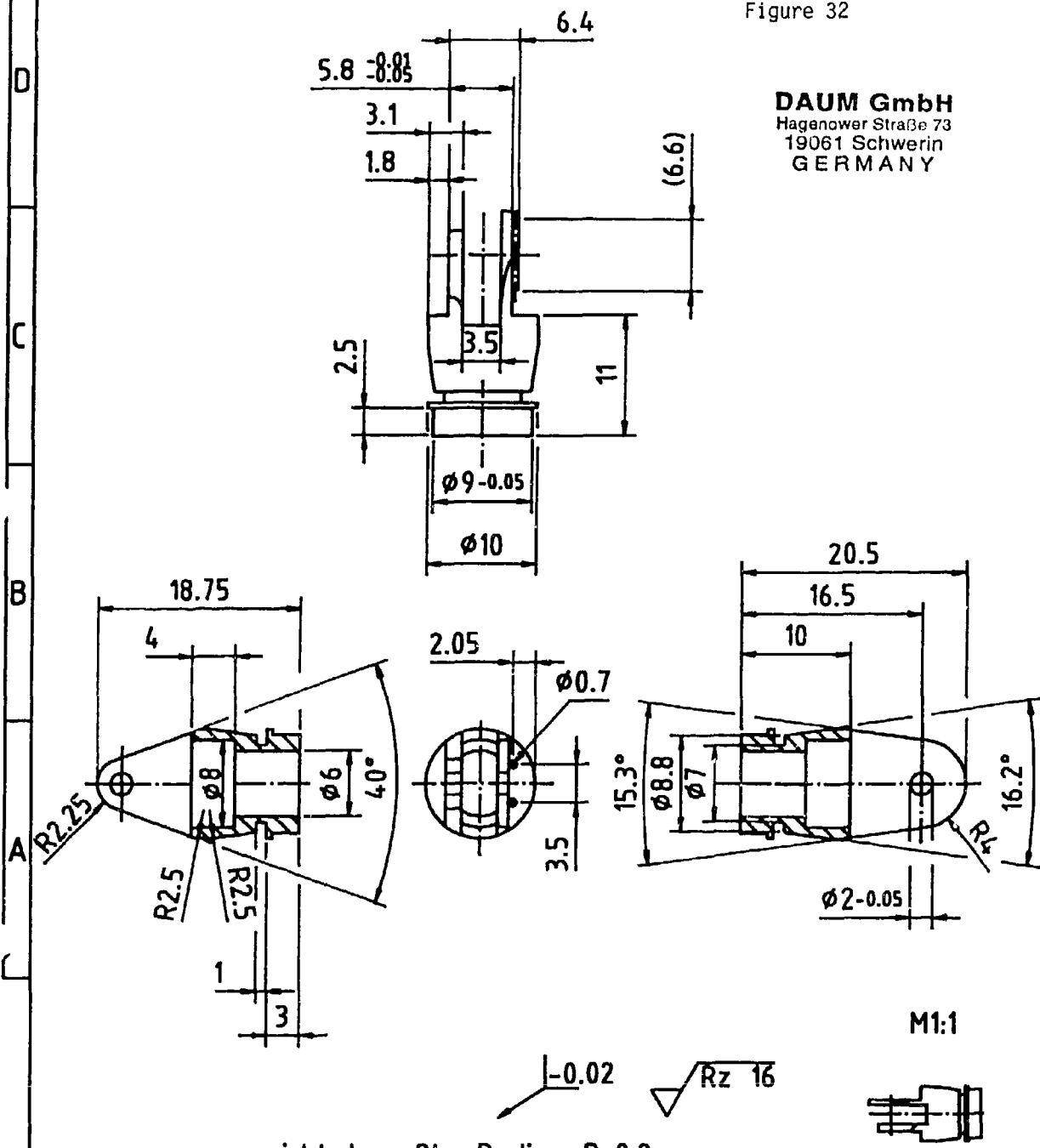
M1:1



				Oberfläche		Maßstab 2:1;20:1	Position	Range 1
DN 2768				fein mittel-grob		-	-	1.4301
				Datum	Name	Gelenk 1		
				Bearb.	06/12/1994			
				Gepr.	27/07/1995			
				Norm				
				Daum GmbH				Blatt
				E000572				Bl.
Zust.	Änderung	Datum	Name	EDV Nr. G:\MECHANIK\TECH\000572				

Figure 32

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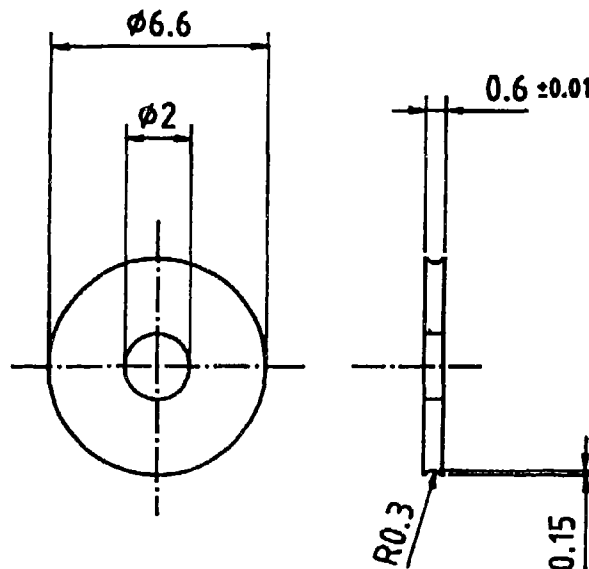


nicht bemaßte Radien R=0.2

				DN2768 fein mittel-grob	Oberfläche	Maßstab 2:1	Position	Menge 1
							1.4301	
			Datum	Name	Gelenk 2			
			Bearb.	aw				
			Gepr.					
			Norm					
				Daum GmbH E000573				Blatt
Zust	Änderung	Datum	Name	EDV Nr. G-MECHANIK/E000573				Bl

Figure 33

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				DM2768 fein mittel-grob	Oberfläche	Maßstab 5:1	Position	Menge 1
						-	1.4:05	
						-		
				Datum	Name	Scheibe		
				Bearb.	08/12/1994 GW			
				Gepr.	26/07/1995 AW			
				Norm				
				Daum GmbH				Blatt
				E000574				Bl
Zust.	Änderung	Datum	Name	EDV Nr. E000574				